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A Study on Distributed Generation with a Focus on Solar Power

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Abstract

Centralized generation is when electric power is produced in a large scale of tens of MWs and is located away from the end user. This kind of production is connected to a series of high-voltage transmission lines. Electricity is then delivered to the end user through a network of distribution grids. Centralized generation tend to have multiple end user with multiple user profiles.

Distributed Generation is when is produced in a small scale and is located at the site of or very close to the end user. There are many ways distributed generation can be achieved, Solar power being the most prominent. Distributed generation is generally assigned to a single end user and a single user type. Examples of distributed generation are solar, small generators and any form of generation with power ratings from KWs to a few MWs.

Centralized generation and distributed generation have many differences between each other. Distributed generation helps in cutting down the line losses that come with having long distribution lines and with having end users located far away from the point of generation. Distributed generation also has many setbacks, includes requiring converters which would help in matching the needed voltage.

This thesis will draw an analysis between distributed and centralized generation. Comparing different types and studying advantages and disadvantages of both. DC-DC converters are studied for the application in distributed generation. Matlab and simulink models of solar application are built and studied with the use of a model DC-DC converter with a mutual conductor. Practical aspects of solar power installation are also studied.

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Chapter 1: Introduction and Literature Review

1.1 Distributed Generation Vs Centralized Generation

Considering that solar and other renewable sources of generation are relatively newer compared to conventional forms of generating electricity, terms such as “decentralized generation”, “dispersed generation” and “distributed energy resources” are still used to define renewable sources of electricity. As show by Pepermans et al. (2005), all these terms have different meanings when the characteristics of each are considered. According to Dondi et al. (2002) any generator that is not part of the centralized generation and is rather smaller in production is defined as Distributed Generation. Chambers (2001), however, limits the maximum amount of generation for a distributed generation as 30 KW.

Distributed generation doesn’t have a proper defined upper limit in literature, therefore the limit can range anywhere from 1MW to 100 MW (Ackermann et al., 2001). For the purposes of encompassing the many definitions and categories of distributed generation, Ackermann et al. (2001) came up with a definition for all types of distributed generation.

“Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter”. (Ackermann et al., 2001).

From the early 1930s centralized generation has been the most sought-after form of generation due to the development of an AC grid. (Carley, 2009). Over the past century, even before the development of AC grids, centralized generation prevailed. This also gave rise to high transmission losses and the generation of high amount of greenhouse gasses. Centralized generation is largely fueled by fossil fuels. Coal power plants (maximum generation) were first used in US and are still being used. Keeping in mind the high amount of power usage by the country there are very high amount of pollution that is being caused by the power plants. Hydro-generation power plants are the second highest power producing type in the US, these have very high ecological effects on the environment and deteriorates the ecological sanctity of a region.

1.2 Drawbacks of centralized Generation

Several literature works circle out the drawback of centralized generation. This helps in expanding motive towards the development of

distributed generation as the main source of power or at least as a source of power complementing the main source of power.
(El-Khattam et Salama, 2004; Perpermans et al., 2005).

Important characteristics from the literature review are discussed further:

Costs due to Transmission and Distribution: Transmission of electricity and distribution of electricity can amount upto 30% of the total cost of electricity. In this scenario, the costs of transmission and distribution for small customers that tend to take electricity at smaller volume and voltage is higher than that of an industrial customer whose demand voltage ranges from medium to high voltage (IEA, 2002).

The costs of transmission and distribution have a few main drivers:

- Conductor resistance and other factors like leakages leading to line losses;
- Theft of electricity ;
- Electricity has to be converted to match with each customer's needs(residential and industrial) This continuous stepping down and stepping up of voltages create losses and inefficiency (EIA, 2009).

Complete amount of losses created is very significant, as shown in table 1. Excluding the amount of financial loss, there is also an implicit loss in terms of greenhouse emissions.

Table 1Transmission and Distribution Losses towards Un-accounted Power Usage in the US. (Energy Information Administration, 2009)

Date	Net Generation-Bn kWh	T&D losses and unaccounted for Electricity	Ln%
1973	1864	165	8.9%
1975	1921	180	9.4%
1980	2290	216	9.4%
1995	2473	190	7.7%
1996	3444	231	6.7%
1997	3492	224	6.4%
1998	3620	221	6.1%
1999	3695	240	6.5%
2000	3803	244	6.4%
2001	3737	202	5.4%
2002	3858	248	6.4%
2003	3883	228	5.9%
2004	3971	266	6.7%
2005	4055	269	6.5%

2006	4065	266	6.5%
2007	4157	264	6.4%
2008	4115	241	5.9%

- Rural electrification: In a large power system with many user profiles, providing electricity in rural areas can be challenging due to many reasons. Long overhead lines need to be developed so that rural areas can be provided with electricity, combining this with a small amount of usage can prove un-economical. The increase of losses which further increases the costs of transmission and distribution also adds on, making providing of electricity to rural places very costly. In cases like these, distributed generation is economically more feasible (Carley, 2009).

- Costs due to expanding transmission and distribution network: Due to the increase in population and the expansion of small towns the investment linked with expanding transmission and distribution networks will increase over the next 20 years. Estimated investment of OECD countries towards the expansion of electricity by The International Energy Agency (2003) is 3000 to 3500 billion dollars by the year 2030. Distributed generation is an alternative in such cases, helping in bringing the costs of transmission and distribution network down.

- Energy efficiency: Gains/profits of energy transmission and distribution started to become smaller and smaller in the 1960s due to the use of higher temperature and pressure. These conditions lowered efficiency and also caused massive wear and tear in the materials that were used, eg: steam engine (Hirsch, 1989). Cogeneration systems were then developed to reuse the heat from neighboring generation plants. This combination of 2 generating facilities, electricity and heat increased efficiency of a plant to about 90% (IPPC, 2007). While generating of electricity solely results to only a 40% efficiency in a plant. This further justifies the use of distributed generation as the transport of heat and electricity is not easy and results in high costs.
- Security and reliability: Energy security is better achieved by using distributed generation as:

Fuel diversity:Centralized generation can accommodate for very few types of fuels, while distributed generation can accommodate many different kinds of generations, which also gives incentive of moving away from conventional sources (IEA, 2002).

Back up generation: one of the most important uses of distributed generation has been to act as a back up at important facilities like hospitals and police stations. Generators have been installed at critical locations to provide electricity in case of distribution/transmission network failures.

- Deregulation of Electricity: In Energy markets which are de-regulated, the reserve electricity of any plant can be depleted due to unplanned shortages, in cases like these the cost of electricity is driven up. To help in situations like these, large consumers have developed distributed generations for themselves. This has been possible only after the market had become more flexible and allows for multiple points of entry.
- Environmental Impact: Conventional fuels for generation of electricity have a huge negative impact on the environment. It amounts to about $1/4^{th}$ of NO_x emissions, $1/3^{rd}$ of CO_2 emissions and $2/3^{rd}$ of SO_2 emissions of the whole of United States(EPA, 2003). Distributed Generation has been used to mitigate some of these

factors including environmental effects caused by transmission and distribution.

1.3 Revival of Distributed Generation

As noticed there are many factors that influence the idea of distributed generation. This is not to remove the method of centralized generation but it is to compliment it. This will help in 2 ways: by eventually leading to the deregulation of the electricity market and by reducing the emission of greenhouse gasses drastically (Perpermans et al., 2005).

To promote distributed generation, Europe released two directives which aimed at providing a free flow of gas and electricity across the continent. Thus, creating a new framework making it possible to increase the share of electricity produced by the method of distributed generation. (IEA, 2002). These directives have led to 2 main advantages for the distributed generation:

1) Due to the recent decentralized energy market changes, distributed generation is able to develop and spread more quickly. New applications include the development of peaking generators and also capacity generators, Peaking generators help mitigate the costs

incurred due to demanding electric power at a time of peak demand prices and capacity generators help in providing electricity in times of higher consumption without having to burden the grid. (Pepermans et al., 2005).

2) Distributed generation is smaller in size and is easier to build when compared to conventional methods, this helps in providing electricity in congested places and also in geographically hard locations. Distributed generation also helps in mitigating the need to provide small amount of electricity to meet demand of smaller consumers (IEA, 2002).

One of the most important impacts that is leading todays distributed generation revolution is to help avoid the kind of impact a centralized generation network has on the environment. The environmental and economic constraints led to the search for a better method of power generation. Distributed energy portrayed positive impact on the abovementioned constraints by:

1) Cogeneration has helped in mitigating the need to store and transport heat/steam, being able to use the heat for centralized heating as well as

production of electricity has helped in reducing costs and has a positive impact on the environment.

2) Distributed generation is flexible in terms of using different forms of fuel. For example, using gasses from a landfill is one of the typical advantages to distributed cogeneration.

1.4 Current and prospective share of Distributed Generation

Distributed generation, as explained in the introduction has many definitions and thus becomes hard to estimate the total amount of distributed generation currently in use. The said differences lead to a varied amount of results, which is due to the dilemma of being able to include a certain type of distributed generation. For example, the exclusion of all distributed energy plants above the range of 20 MW brings California's share of Distributed generation down to 2.5% while the inclusion brings the share upto 17% (Rawson and Sugar, 2007).

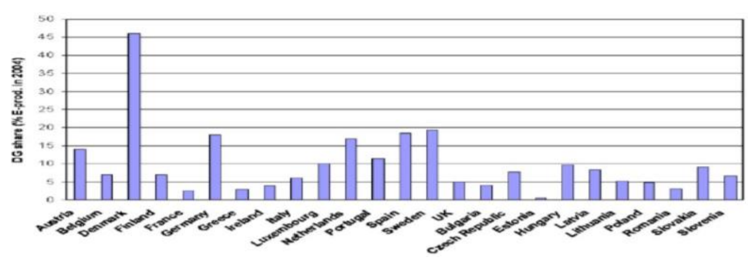

Figure 1 Distributed Generation share by the 25 countries of EU. (Cossent et al., 2009).

Chapter 2: Distributed Generation

2.1 Constraints

Classifying what amount of generation is distributed generation and what amount of power generated would be not be considered as distributed generation was and still is a significant problem. This hampers in the growth of a network that is robust and reliable. For example, during the year 2007, in the state of California the amount of distributed generation was 2.7% of the total demand. This 2.7% is when co-generation of above 20MW was not considered. From the same data when all levels of co-generation were considered, the share went up to 17% of the total demand (Rawson and Sugar, 2007). `

Furthermore, estimation of the amount of co-generation that penetrates the main utility grid at an instant of time is difficult and hence decreases the robustness of the framework that is being developed to accommodate both central and distributed generation, as noted below.

> **"**For a long time, western Denmark managed to increase DG connection apparently with only minor changes in network control. […]. It was not until the early 2000s that the reliability problems, created by the sudden increase in wind generation, grew acute—notably the blackouts in eastern Denmark in 2003 were a wake-up call." (Lethonen and Nye, 2009) -

2.1.1 Technical Constraints

To develop a robust framework that would be able to accommodate and reciprocate to any or most amount of renewable power, recognizing and overcoming of technical constraints is the initial step.

The following is a discussion of the technical difficulties involved in employing distributed generation (Pehnt and Schneider (2006)).

1) Capacity of Distributed Generation: When Distributed Generators are added at the distribution network level, it creates a lot of load on the pre-existing distribution network (transformers and conductors). Work for reinforcing the pre-existing network is to be undertaken. One of the most important pieces of the network is the transformer which converts medium voltage to low voltage and high voltage to a medium voltage level. When the power generated by the distributed generator is far higher than the consumption then the voltage will have to be converted from low to medium and then to high voltage so it can be directed to other areas of consumption. A transformer needs to be equipped with handling this kind of flow (and have the ability to handle a potential overflow). Considering the times during peaking hours, the distributed generators are at their maximum output to be able to make a difference during peak demand and

also the continuous distributed generators, the transformers and conductors need to be equipped this kind of flow.

Determining the transformer's and the cable's specifications can also be done with a demand forecast during peaking hours as this will be the time of maximum power flow.

2) Power: Distributed generators are connected generally in low voltage networks. This allows for the voltage to be maintained in long distribution lines. In long distribution lines the power losses are higher due to the added-up resistance in the cables. Though distributed generators help in keeping the power levels maintained and help in delivering the required amount of power they cannot cross a certain threshold. When a distributed generator is connected to a network which is already at threshold, it causes a negative impact on the whole distribution network

3) Protection: For the connection of distribution network, it needs to be developed so that the grid associated strictly with the distributed generation isolates itself any-time there is an internal fault (Jenkins et al.,2000). This also operates in a way where the distribution grid is still functioning while a few parts are not functioning. This works in favor of the customer. When there is a deficit in power in the centralized grid, power from the distributed

generation network can be used to satisfy the needs of the end user. In this way power security is developed.

4) Transients: The distributed generation network interchanges functions from being connected to the main grid and functioning independently. This gives rise to transient currents in the main grid.

5) Losses in Transmission/Distribution Network: Of the many advantages of Distributed generation, helping in maintaining the voltage level reduces the amount of losses in the distribution network. In a few cases where a consumer has a distributed generation network for one's needs the load on the distribution network decreases and significantly reduces losses. But, in a case of high penetration of distributed generators, the effect is heavily detrimental to the distribution network (Mendez et al., 2002).

2.1.2 Regulatory Barriers

After understanding the major technical challenges that distributed generation possess, a study of regulatory barriers is made in this section. This section will give be an introduction towards the regulatory barriers and a few types of cost implications distributed generation has.

When an operator of a distributed network is seeking connection with the utility grid, the operator pays a certain amount of fee to the utility grid. The charges can be a onetime fee which shows as remuneration towards the physical connection. Or this can also be a repeatable fee charged upon usage of services. This fee is called the Network Tariff (Cossent et al. (2009)).

This network tariff can be further divided into deep and shallow connection charges. Deep connections can be defined as a connection where the distributed generator pays for connections and the upstream network reinforcements. In shallow connection charges the DG pays only the connection charges (Cossent et al. (2009)).

Tariffs such as Use-of System charges are quite low and do not cause a hinderance to distributed generators, the tariff is favorable to the distributed generators. However, as the penetration of distributed generators increase the use of system charges will become different. The choice of being able to connect to deep and shallow networks will impact the distributed generation as the penetration level gets higher. Distributed generation will be affected by the deep connection charges as after a point the net investment impact of distributed generators in deep connections will become negative. The following section of this paper will study the economics of distributed generation.

2.2 Economics of Distributed Generation

Cost-competitiveness is one major problem that distributed generation will have to overcome. These parameters vary however from one kind of distributed generation to the other. As seen from the table below, distributed generation has very low costs or even highly comparable costs in comparison to combined cycle gas turbines. Due to the cheap costs of coal, coal steam turbines are still comparable to other sources of generation but have a very high capital costs. When compared on a KWH basis, the distributed generation methods are not the best. The way to look at the picture is by factoring in more parameters. The ability of distributed generation to produce both heat and electricity will modify the outlook. This will bring distributed generation higher in terms of economic benefit than centralized generation by having removed the costs of adding a completely new boiler to the pre-existing plant (Strachan et Farell, 2006).

Table 2 Different cost implications of types of Distributed generation. (Strachan et Farell, 2006)

	Efficiency(% HHV)	Unit size(MWe)	Capital Cost($/KW)	Fixed O&M cost($/KW-ys)	Variable cost (C/KW)	Fuel Production Cost (C/KWH) 1999 Average	Fuel Production Cost (C/KWH) 2001 Average
Gas Reciprocatin g engines	29	0.2	750	15	1	0.68	1.19
Diesel-Reciprocatin g Engines	35	0.2	700	15	1	1.05	1.44
Microturbine	25	0.06	800	15	0.6	0.68	1.19
Fuel Cell	38	0.1	3000	15	0.6	0.68	1.19
Gas Turbines	29	10	480	15	0.55	0.68	1.19
CCGT(Central ized Generation)	50	200	550	15	0.55	0.68	1.19
CST (Centralized Generation)	33	500	1100	15	0.4	0.38	0.42

Heat to power ratio is defined as the ratio of energy produced or consumed in form of heat and energy produced or consumed in form of electricity.

$$HPR = \frac{\text{Energy produced or consumed in form of heat}}{\text{Energy produced or consumed in form of Electricity}}$$

When the heat to power ratio of any generation is 0 then only electricity is produced in that technology. A heat to power ratio of 2 is reached when a facility is in need of 2 times the amount of electricity in the form of heat. As the steam turbine technology does not operate at maximum efficiency, the distributed generation facilities will always have a positive impact as the HPR ratio goes up. As the HPR increases the curve starts to converge and the system is no longer able to have co-generation and an extra boiler has to be installed for the purpose of co-generation, hence driving the costs up. At high HPRs the costs area effected only due to the addition of an extra boiler but distributed generation does not drive up the cost.

2.3 Types of Distributed Generation

The varied amount of end-user profiles gives way to a varied amount technologies. There area many technologies that come in the range of Distributed generation, defined by International Energy Agency (2002) as:

1) Reciprocating Engines: Reciprocating engines use an age-old method to ignite a combustible mixture under pressure to move a piston. The mixture contains compressed air and fuel. This technology is old and is still very effective due to the low capital cost induced and low maintenance costs. Here mainly combustion was used to move a piston therefore helping convert chemical energy to mechanical and then further to electrical energy. Many reciprocating engines run on different combustible fuels and have recently started the use of bio-gas as a fuel. Many reciprocating engines are used as a peaking generator due to their small size(45% in the year 2007-2008), the rest are used as back-up and emergency generators, the main drawbacks include high noise and air pollution(IEA, 2002).
2) Gas Turbines: As natural gas started to come-up as a good fuel alternative, due to their low emissions, gas turbines started to be used more widely. The government provided incentives also helped in the vast wide-spread of gas turbine technology. As a contrary to the reciprocating engine, during the year 2007-2008 gas turbines were more used as

continuous generators (DGTW, 2008). The main advantage to the gas generation technology is the ability of co-generation, micro-turbines are a part of the gas turbines but developed for smaller power needs and operate at higher operating speeds.

3) Fuel cells: Fuel cells is a newer technology and is still in the R&D process, this technology converts the chemical energy of a fuel directly to electrical energy which can further be used by an end user. Fuels used for this are natural gas and hydrogen. High capital costs and low efficiency are the 2 main drawbacks of this technology.

4) Renewable sources: Renewable sources of energy, in recent history, been used as distributed generation widely. The positive environmental impact when compared to conventional methods has been a major driving force in the widespread of this technology. Wind-turbines, Solar systems and thermal energy have been the 3 main types of renewable resources. High initial capital needed has been a drawback for this technology. Drawbacks also include the ambiguity of definitions, such as an offshore wind farm wouldn’t qualify as a distributed generation facility. (Perpermans (2005))

2.4 Impact on Climate

Distributed generation has many types and doesn't always mean clean energy. Figure 3 gives the emissions comparison between gas and diesel reciprocating engines, microturbines, fuel cells, combined cycle gas turbines and coal steam turbines. The emissions produced by a boiler have been added to make it possible to compare the emission of centralized generation with an extra boiler used on site for heat and distributed cogeneration.

Table 3 Different emissions of types of generation. (Strachan and Farell, 2006)

	CO_2(g/kWh)	SO_2(g/kWh)	NOx(g/kWh)	CO(g/kWh)	PM_{10}(g/kWh)	HC(g/kWh)
Gas Reciprocating Engine	625	0.032	0.5	1.8	0.014	0.54
Diesel reciprocating Engine	695	1.25	2.13	2.8	0.36	1.65
Micro-Turbine	725	0.037	0.2	0.47	0.041	0.14
Fuel Cell	477	0.024	0.015	0	0	0
Gas-turbine	625	0.032	0.29	0.42	0.041	0.42
CCGT	363	0.019	0.195	0.07	0.041	0.05
CST	965	5.64	1.7	0.07	0.136	0.05
Gas-Fired Boiler	201	0.01	0.12	0.12	0.01	0.014

Diesel reciprocating engines are the worst emitters in terms of nitrogen oxides (NOx). Combined cycle gas turbines tend to be the best performers in terms of carbon dioxide (CO2), Sulphur dioxide (SO2) while fuel cells are the lowest emitters when it comes to NOx, CO, particulate matters (PM10) and hydrocarbons (HC) (Strachan and Farell, 2006).

Distributed generation is not always the best performer in terms emissions. Though some technologies such as fuel cells seems promising for future application, the absence of implementation background and the costs of this technology are still hindering its diffusion on a large scale. To be used in the cleanest way possible, distributed generation will thus have to use the less emitting technologies and favor renewable power.

2.5 Solar power

There is an immense amount of need and room for the build of solar power as distributed energy. As seen before there are many other types of distributed generation which help in reinforcing the network. HPR ratio generally ranges from 0 to 2, where 0 is an ideal condition. The HPR ratio for solar power is less than 1.

Section 2.2 also describes the different costs that are created due to the use of different types of distributed generation, in the figure 4 a price chart of solar power is included:

Here it is observable that the costs related to solar power are significantly decreasing and when compared to the costs of other sources are much lesser.

Table 4 Cost implications of Different sources of Power

Value Category	2009 Study Potential Value (Cents/kWh)	2013 Study Potential Value (Cents/kWh)
Distribution System	0 to 0.31	0
Transmission System	0 to 0.51	0.32
Generation System	0 to 1.85	1.66
Fixed O&M	0.81 to 3.22	0.29
Fuel, Purchased Power, Emissions and Gas transmission	7.10 to 8.22	5.93

Solar power comes with own technical constraints. While producing solar power for an off-grid system, the power produced from the solar panels needs to be filtered through a converter to match the needs of the end user. In a grid connected system, the solar power need to have an immense amount of voltage amplification to match the voltage in the transmission lines to be able to sell back power to the utility grid.

Federal Government extends a tax credit of 30% to any person installing solar in a small amount. Other incentives include, net metering. Net-Metering is where unused or excess power is sold from the distributed generation to the utility grid. Incentives like these make solar power a viable option for having a drastic change in the paradigm of power generation and transmission.

2.6 Summary

Chapter 2 introduces the concepts of Distributed Generation in depth. It is seen that distributed generation does not always need to mean renewable power or clean power. There are many emissions that are produced by distributed generation methods as well. Chapter 2 also introduces solar power and renewable power as a viable option towards developing a distributed generator network. It has little to no emissions and has many incentives when installed even in small amounts.

Moving forward, this thesis will study and test a novel DC-DC converter. As there is need of the voltage being raised so that solar power can co-generate and synchronize with the utility grid a method to do that will be studied.

Chapter 3 will introduce the different types of DC-DC converters. Chapter 4 will study and test the focused converter in question and draw a conclusion towards usage in harnessing and maintaining solar power. Chapter 5 is for study of practical solar power installation.

Chapter 3 DC-DC converters

A DC-DC converter is a circuit that converts low/high voltage to high/low voltage. Generally, the output voltage is set to exceed the AC voltage level of the grid. This voltage is used as input to an inverter, which then converts the DC voltage to AC and feeds it to the grid. DC-DC converters are used to maintain DC power, decrease fluctuations and provide a reliable connection to a high voltage line. Solar power is DC power therefore, a DC-DC converter is required to adjust voltage for the end user.

Buck, boost and buck-boost converters are three types of converters. In these circuits, power devices are used as switches. This device earlier used was a transistor, which is turned on by a pulse fed at its gate. In all these circuits, the transistor is connected in series with load to a dc supply, or a positive (forward) voltage is applied between anode and cathode terminals. The thyristor turns off, when the current decreases below the holding current, or a reverse (negative) voltage is applied between anode and cathode terminals. So, a thyristor is to be force-commutated, for which additional circuit is to be used. Earlier, dc-dc converters were called ‘choppers’, where thyristors or GTOs are used.

Here, buck converter (dc-dc) is called as ‘step-down chopper’, whereas boost converter (dc-dc) is a ‘step-up chopper’. With the advent of bipolar junction transistor (BJT), which is termed as self-commutated device, BJT is also used as a switch instead of thyristors in dc-dc converters.

3.1 Buck Converter

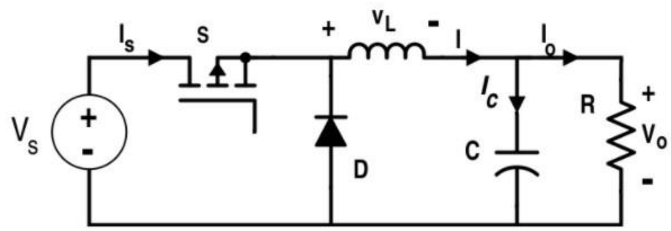

Figure 2 Buck Converter (M H RASHID, 2007)

Here, the DC supply is V_s. There are 2 control switches, diode D and power electronics switch S. Further, it is a 2 pole low pass filter with a L(inductor) and C(capacitor) circuit.

The duty cycle of the circuit is:

$$D = \frac{T_{ON}}{T}$$

(3.1)

Here, $T = Ton + Toff$

(3.2)

The circuit can be studied in 2 modes. Mode 1 is when switch S is off and mode 2 is when switch S is on.

Mode of operation:

• When switch is ON:

Voltage across the inductor equals to

$$VL = L\frac{(di)}{dt}$$

(3.3)

Here, $I = Ic + Io$ (3.4)

Load Current equals to $Io = \frac{Vo}{R}$

(3.5)

Applying KVL,

$$VS = VL + VO$$

(3.6)

$$\Rightarrow VS = \frac{Ldi}{dt} + VO,\ VO = VC$$

(3.7)

• When switch is OFF:

The KVL becomes,

$$VL + VO = 0$$

(3.8)

$$\Rightarrow VO = -\frac{Ldi}{dt}$$

(3.9)

As the output voltage is assumed constant by the small-ripple approximation,

$$\Rightarrow \frac{Ldi}{dt} = constant$$

(3.10)

$$\Rightarrow di/dt = constant$$
(3.11)

Waveforms of voltage and current of buck converter within the one-cycle period are shown in Fig. 6:

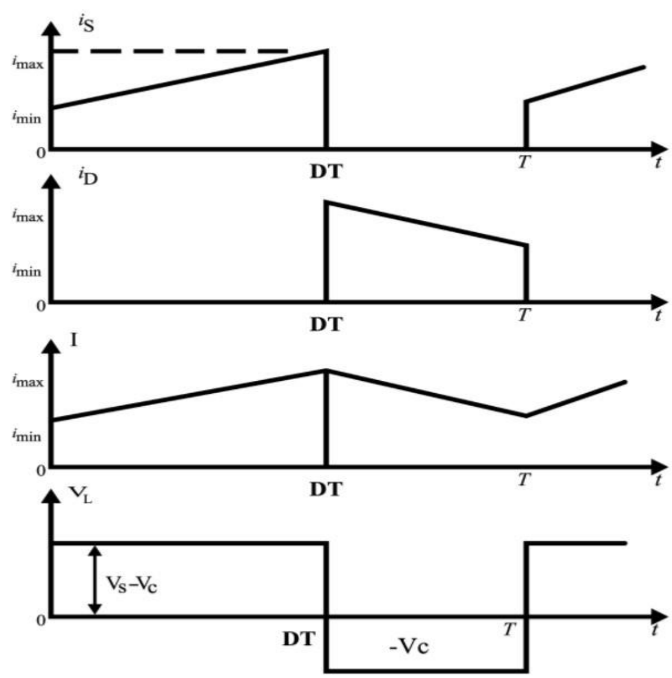

Figure 3 Supply Current Is, Diode Current ID, Inductor Current I, and Inductor Voltage VL Waveforms respectively (Buck Converter) (M H Rashid 2007)

Because, $VL = \frac{Ldi}{dt}$

(3.12)

$$\Rightarrow (Imax - Imin)SWITCH - ON = \frac{VS - VO}{L} dt$$

(3.13)

$$(Imin - Imax)SWITCH - OFF = -\frac{VO}{L}(1 - dt)$$

(3.14)

$$\Rightarrow Average\ Inductor\ Current = \frac{Imax + Imin}{2} = I$$

(3.15)

According to Fig. 3 and from the steady-state perspective, magnitude of the inductor current increment during switch on is equal to the inductor current decrement during switch off; i.e.

$$|(Imax - Imin)SWITCH - ON| = |(Imax - Imin)SWITCH - OFF|$$

(3.16)

$$\Rightarrow |VS - VOLDT| = |-VOL(1 - DT)|$$

(3.17)

$$\Rightarrow V_O = DV_S$$

(3.18)

In the case of the buck converter, output voltage directly depends on the duty cycle and the voltage(input).

Alternatively, this can also be derived as follows:

As the net current passing through the inductor is 0,

$$I(T) - I(0) = 0 \quad (3.19)$$

$$\Rightarrow \frac{1}{L}\int_0^T V_L dt = 0 \quad (3.20)$$

3.2 Boost Converter

Figure 4 shows structure of a boost converter:

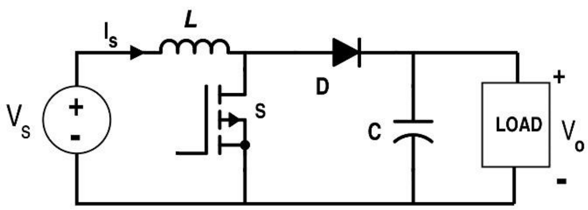

Figure 4 Boost Converter (M H Rashid 2007)

- When the switch is ON:

$$VS = VL \tag{3.21}$$

$$\Rightarrow L\frac{di}{dt} = VS = Constant\ supply\ voltage \tag{3.22}$$

$$\frac{di}{dt} = c, \text{ here C is constant} \tag{3.23}$$

This shows current that flows through inductor L increases with constant slope, when switch S is ON.

- When switch S is OFF:

$$\Rightarrow VS = VL + VC \tag{3.24}$$

$$\Rightarrow L\frac{di}{dt} = VS - VC; \tag{3.25}$$

$$\Rightarrow \frac{di}{dt} = (VS - VC)L$$

(3.26)

In this case, current that flows through inductor decreases and can reach a value equal to the value of current at the first stage when switch S is on.

$Current\ increment\ during\ switch\ on = Imax - Imin = VSLdt$

(3.27)

$Current\ decrement\ during\ switch\ off = Imin - Imax = VS - VCL(1 - D)T$ (3.28)

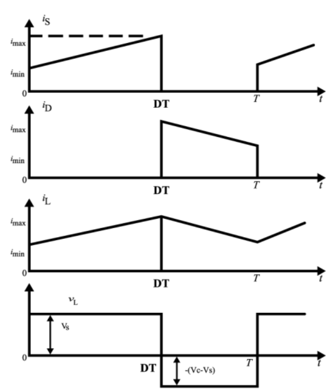

Figure 5 Supply Current, Diode Current, Inductor Current and Inductor Voltage respectively (Boost Converter) (M H Rashid 2007)

3.3 Buck-Boost Converter

A buck-boost converter is capable of handling both the functionalities of increasing the input voltage and also decreasing the input voltage.

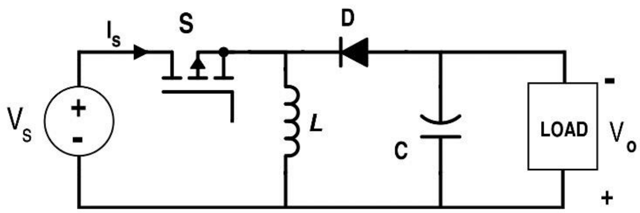

Figure 6 Buck-Boost Converter (M H Rashid 2007)

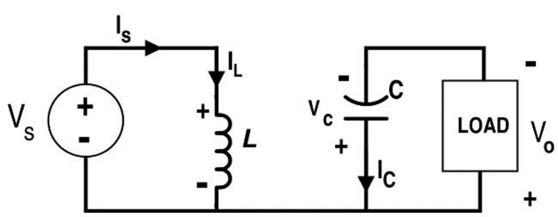

Figure 7 Buck-Boost converter when switch is ON (M H Rashid 2007)

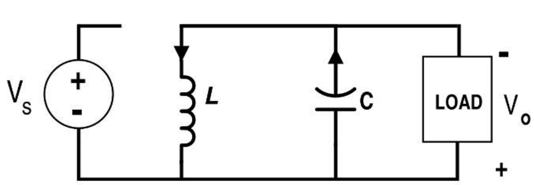

Figure 8 Boost converter when switch is OFF (M H Rashid)

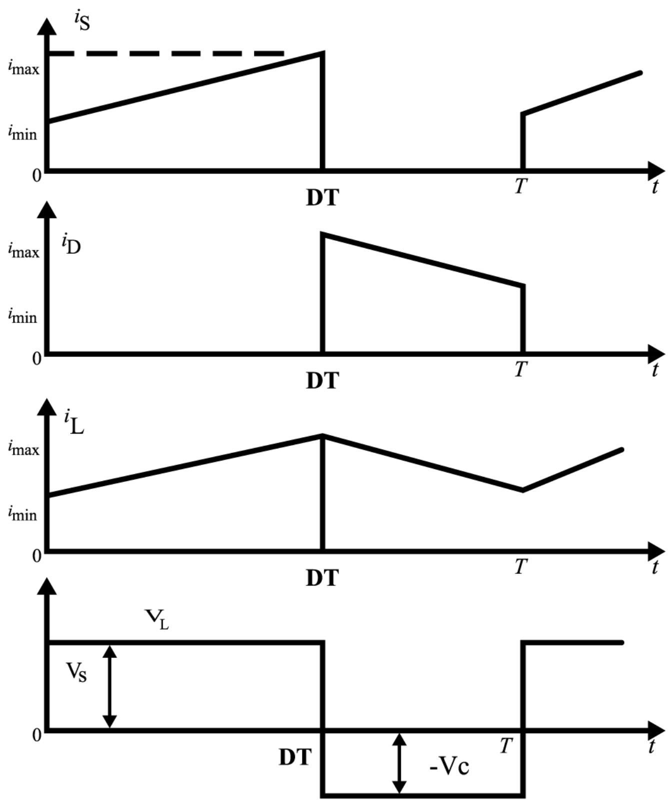

Figure 9 Current and Voltage Characteristics (M H Rashid 2007)

- Output voltage of buck-boost converter is: $V_O = \frac{D}{1-D} V_S$
- When D < 0.5, it acts as a step-down converter or a buck converter.

- When D > 0.5, it acts as a step-up converter or a boost converter.
- And when D = 0.5, input and output voltages are the same i.e. $V_O = V_S$.
- That is why buck-boost converters are also called as DC transformers due to the same role in the case in AC.

3.4 Proposed DC-DC converter for case-study

3.4.1 Converter Description

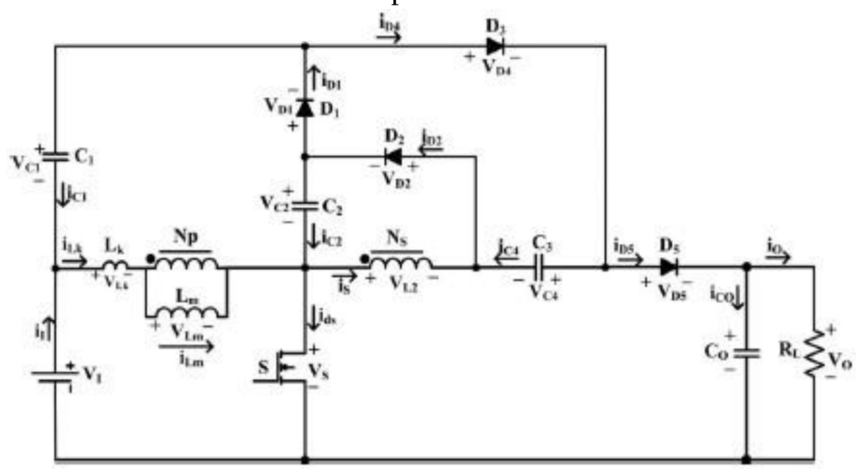

Figure 10 DC-DC converter with coupled Inductor (J H Lee et al. 2014)

The circuit of DC-DC converter with coupled inductor is shown in figure 3.1.

Components of the circuit includes:

1) Input (DC) voltage
2) 4 capacitors
3) 4 diodes
4) 1 Switch (S)
5) 1 Load (R_L)
6) 1 Coupled inductor, which is configured as an ideal transformer. The transformer also comprises of magnetizing inductor and leakage inductor.

The capacitor and diode, C_1 and D_1 act as the clamp circuit. C_2 and D_2 are devices of voltage multiplier for the capacitor C_1. The transformer has a turn ratio equal to N_s/N_p which is also denoted by N.

Assumptions considered for the operation of the Converter are stated as follows:

1) The capacitors in the circuit (C_1, C_2, C_3, C_0) are large and hence the voltages associated with the capacitors are constant during one mode.
2) All components in the circuit are considered ideal.
3) Coupled inductor also has leakage inductance.

The converter under assumptions above contains of 5 stages in one switching period. These 5 stages are all analyzed under Continuous

Conduction Mode (CCM) operation of the converter. Every stage of the CCM mode is related to either charging or discharging of capacitors. CCM in this converter delivers high voltage gain which can be used in solar energy generation system where the voltage input is small.

3.4.2 Stages of Operation

CCM contains 5 stages of operation:

Stage 1:

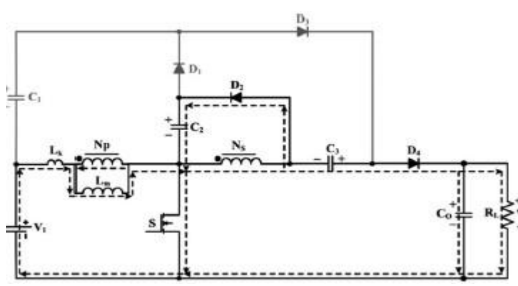

Figure 11 Stage 1 of CCM (J H Lee et al. 2014)

In stage 1 of its operation, which lasts between t_0 and t_1 ($t_0<t<t_1$), switch S is turned on along with diodes D_2 and D_4. Simultaneously the first diode(D_1) and the third diode(D_3) are switched off. The voltage source V_i magnetizes the magnetizing inductor

L_m. Capacitor C_2 and diode D_2 are parallel to the secondary side of the coupled inductor. This causes the current at switch S to decrease linearly as the leakage inductance increases linearly. The necessary load R_L is realized by the capacitor C_0. This stage ends when the current of coupled inductor becomes 0 ($t=t_1$).

Stage 2:

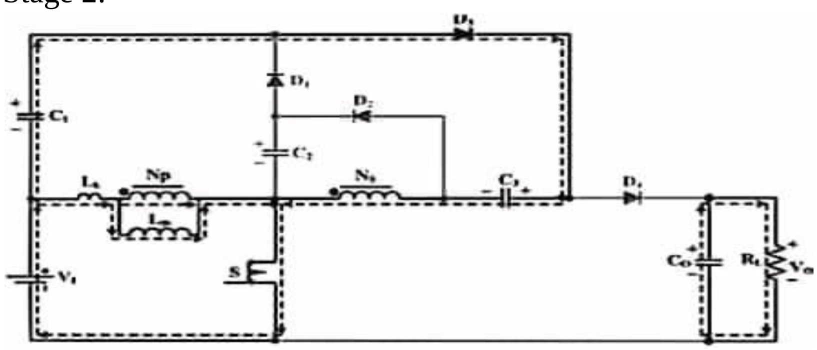

Figure 12 Stage 2 of CCM (J H Lee et al. 2014)

Time: $t_1<t<t_2$

Components that are turned ON: S and Diode D_3.

Components turned OFF: D_1, D_2,D_4.

In this stage the magnetizing inductance in magnetized through the switch S. Therefore, the currents associated with both leakage and magnetizing inductance increase linearly. The source V_i , capacitor C_1 and the secondary side of the inductor are used to charge the capacitor C_3 . The output of the converter is supplied through the output capacitor C_0.

Stage 3:

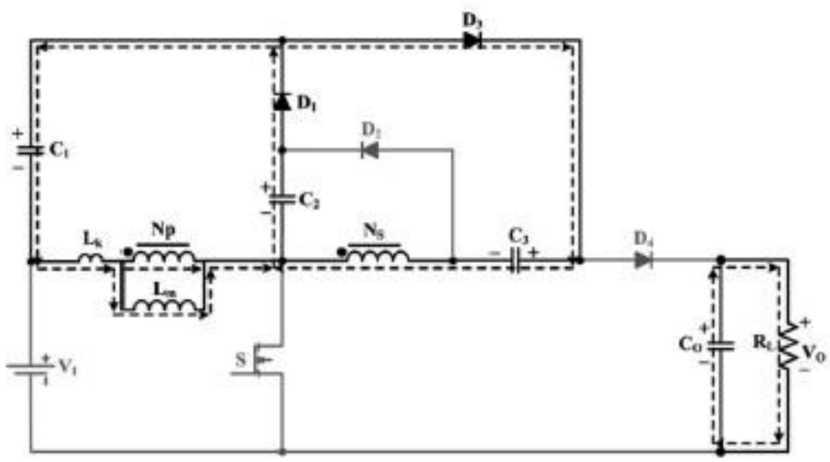

Figure 13 Stage 3 of CCM (J H Lee et al. 2014)

Time: $t_2<t<t_3$

Components turned ON: Diode D_1 and Diode D_3.

Components turned OFF: D_2,D_4.

In this stage the capacitor C_1 is charged by the stored energy in capacitor C_2 and the inductors L_m and L_k. the switch current Is and the current at leakage inductor increases and decreases respectively, the capacitor is still charged through the diode 3. This stage continues till the currents of leakage inductor and magnetizing inductor are equal.

Stage 4:

Time: $t_3<t<t_4$

Components turned ON: Diode D_1 and Diode D_4.

Components turned OFF: S, D_2, D_3.

Here the capacitor C_1 is still charged by the components mentioned in the above stage. The currents in the leakage and magnetizing inductors are decreasing in this stage. The energy stored in the magnetizing inductor is transferred in parts to the secondary side of the transformer. Further the capacitor C_0 is charged by the source, capacitor 3 and also secondary and primary sides of the coupled inductor. This interval is closed by switching D_1 off.

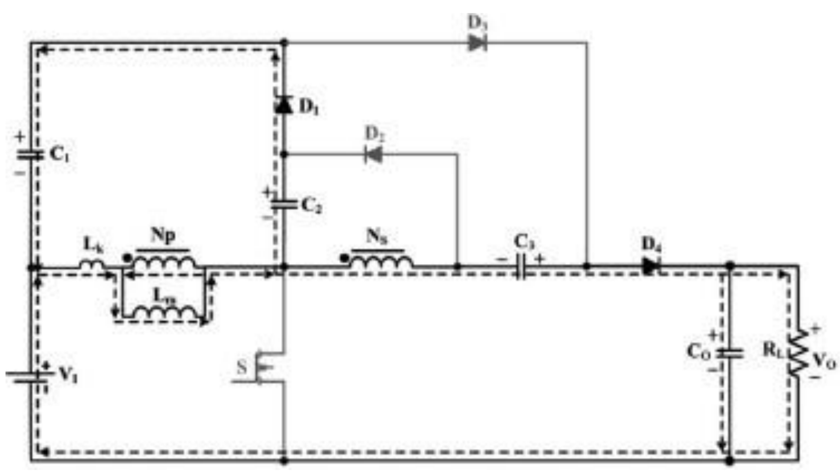

Figure 14 Stage 4 of CCM (J H Lee et al. 2014)

Stage 5:

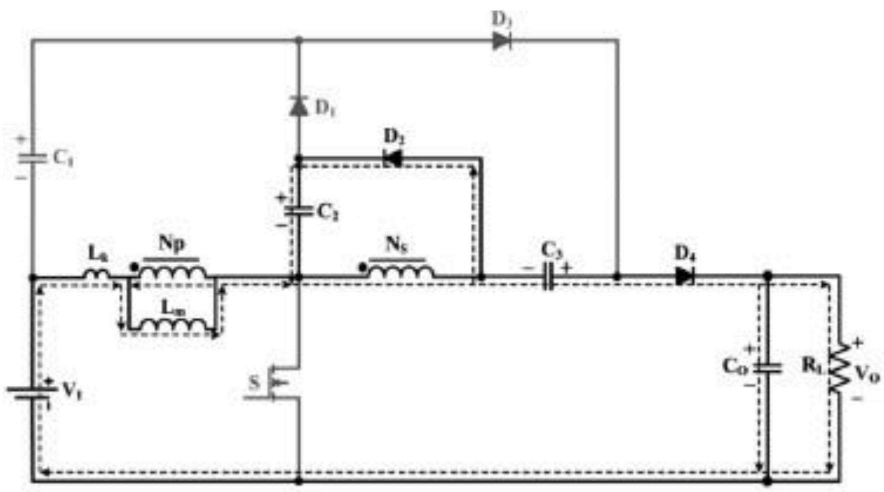

Figure 15 Stage 5 of CCM (J H Lee et al. 2014)

Time: $t_4<t<t_5$

Components turned ON: Diode D_2 and Diode D_4.

Components turned OFF: S, D_1, D_3.

This is the last stage of the CCM switching cycle. The currents in inductors L_m and L_k are still decreasing linearly. To charge the capacitor 2 stored energy from magnetizing inductor is used, this is why the energy is transferred in parts from the previous stage to this. Furthermore, to provide the required amount of output power the ouput capacitor is charged through the VI source, secondary and primary side of the inductor and also the capacitor 3.

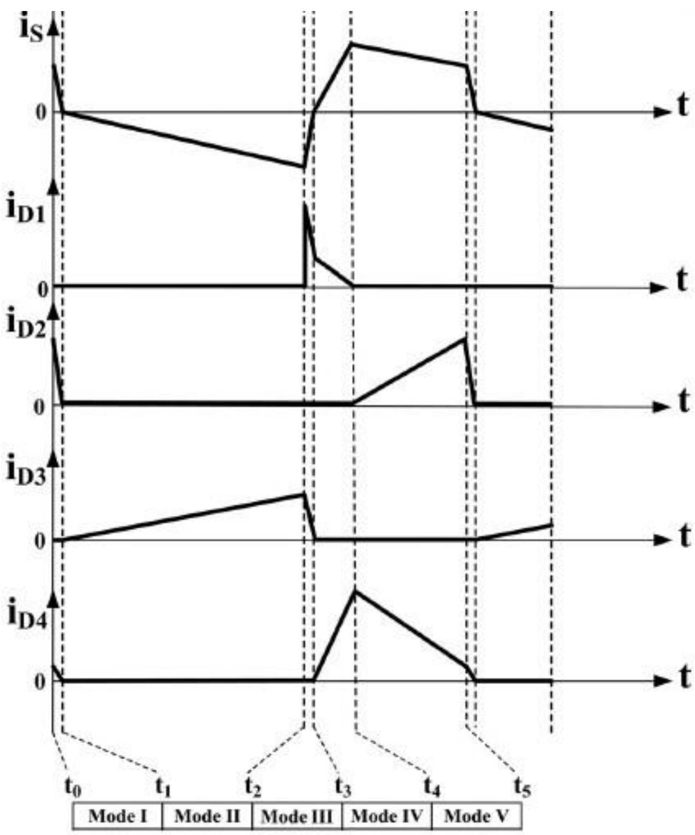

Figure 16 Waveforms of CCM operation of Converter (J H Lee et al. 2014)

3.4.3 Analysis of Modes of Operation

In analyzing this mode of operation only the stages 2, 4 and 5 are considered as the stages 1 and 3 are very small when compared to the stages being considered.

In stage 2 the DC source charges the magnetizing inductor. Therefore,

$$VLm = KV1$$

(3.29)

Here K is the coupling coefficient of the inductor.

$$K = \frac{Lm}{Lm+Lk} .$$

(3.30)

C_3 is Charged by C_1, DC source and also the inductor. This gives rise to

$$Vc3 = VC1 + (Kn + 1)V1$$

(3.31)

Here the n symbolizes the turn ratio of the inductor. Furthrt in stage 4, the magnetizing and leakage inductors charge capacitor 1 through capacitor 2. Hence voltage across the magnezing inductor can be written as

$$V_{Lm} = k\,(V_{C2} - V_{C1})$$

(3.32)

Also, the output voltage can be formulated as

$$V_O = V_I + V_{C3} + (kn + 1)(V_{C1} - V_{C2})$$

(3.33)

In the time interval of stage V, the voltage across Lm can be expressed by

$$V_{Lm} = -\frac{V_{C2}}{n}$$

(3.34)

Moreover, the output voltage is derived as

$$V_O = V_I + V_{C3} + \left(\frac{1}{kn} + 1\right) V_{C2}$$

(3.35)

According to the considered assumptions, the output capacitor voltage is constant during one complete cycle. Therefore, by equating 3.32 and 3.34 we can derive the output of capacitor 1:

$$V_{C1} = \left(1 + \frac{1}{kn}\right) V_{C2}$$

(3.36)

Using the volt-second balance principle on *Lm* and equations (1), (3), (6) and (8),

the voltages across capacitors $C1$ and $C2$ is obtained as

$$Vc1 = \frac{(kn+1)D}{1-D} Vi$$

(3.37)

$$Vc2 = \frac{knD}{1-D}$$

(3.38)

Considering the output voltages of the capacitors C_1 and C_2, i.e. considering the equations 8 and 2 we can derive the output voltage for capacitor 3

$$Vc3 = \frac{(kn+1)}{1-D} Vi$$

(3.39)

Considering equations 10 and 11 and substituting them in the output voltage equation we will be able to derive the value of voltage gain.

$$Mccm = \frac{(2+kn+knd)}{1-D} Vi$$

(3.40)

After having analyzed the modes of operation of the, figure 17 will show the projected performance graph when compared to other converters.

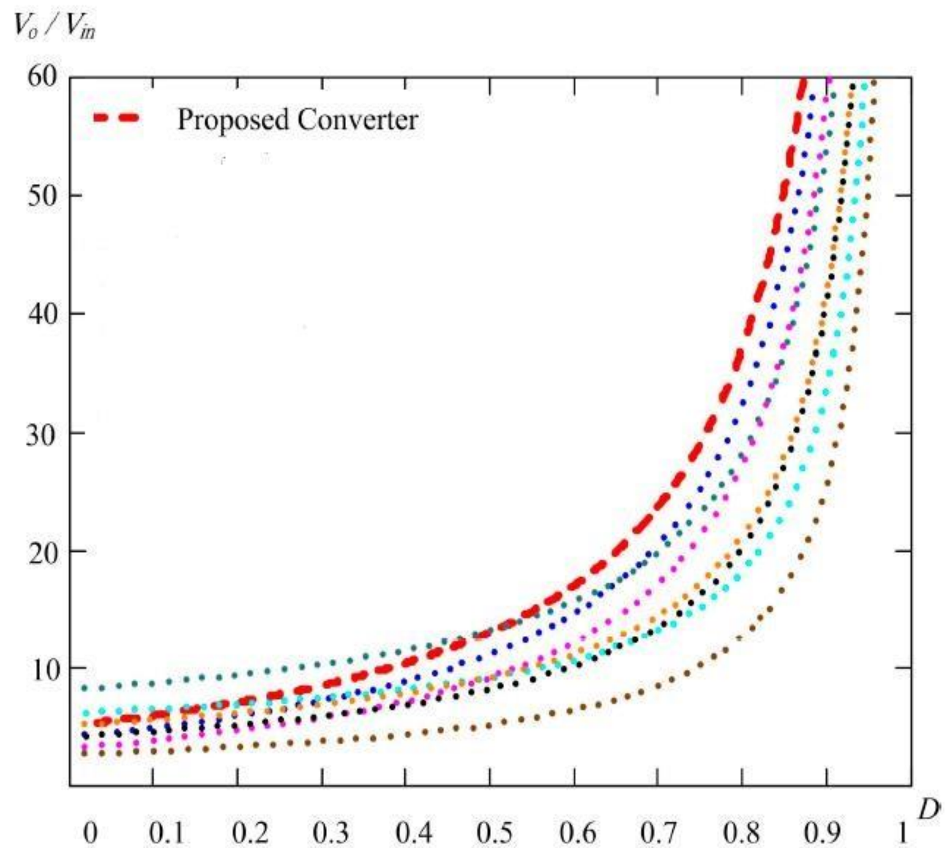

Figure 17 Shows the different performance graphs of converters. (J H Lee et al. 2014)

From the above graph, the voltage gain of the controller with coupled inductor is higher than the voltage gain in converters in other papers. This voltage gain can be helpful in places where the solar production is very low. Furthermore, the converter can help charge a battery. In the coming sections the Simulink model of the converter under the influence of a DC input will be studied. The converter's applications in renewable energy when connected/ disconnected with storage at different quantity is shown and studied.

3.5 Testing the Converter on Distributed generation (Battery)

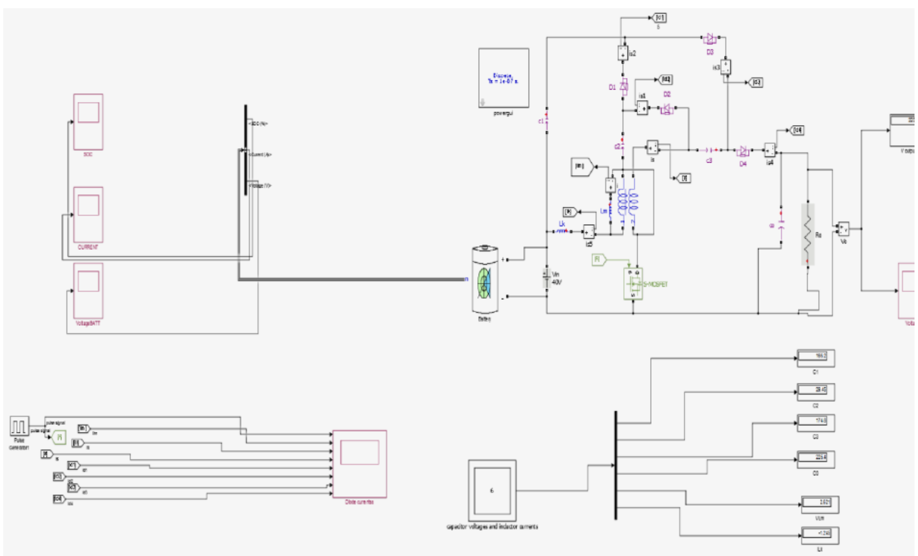

Figure 18 Proposed converter with battery

1) $Voltage$: $40v$
2) Battery: Nickle-Metal Hydride, Nominal voltage is 1.2v
3) Capacitances: C_1=47μF=C_2, C_3=100μF, C_4=220μF
4) Inductances: L_m=300μH, L_k=1μH

5) All 4 diodes have the same forward voltage of 0.8 V.

6) Output Resistance= 533 ohms

Output Characteristics:

As this thesis is making a case study of renewable energy applications for a DCDC converter with coupled inductor, the charging characteristics of the battery along the delivered output voltage is measured.

The battery is considered fully drained as to check how the battery is charging, to measure the credibility of the charge the state of charge of the battery is measured over the sampling time of the simulation. The capacitor voltages with the different diode currents is also measured, these values show how the converter works and defines the charging and discharging of certain capacitors. From the graphs it will also be observable that the output capacitor is C_0.

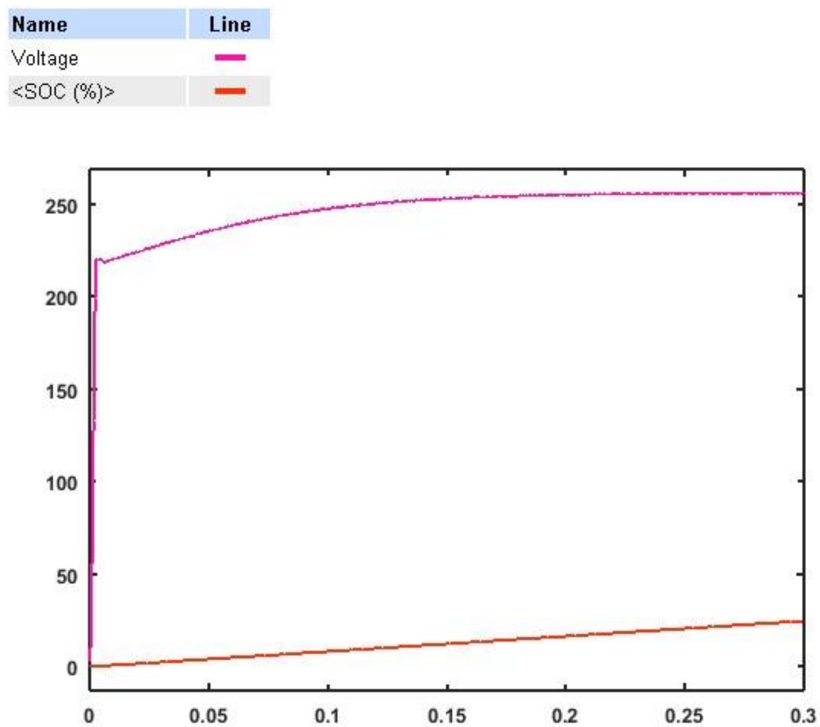

Figure 19 output voltage of converter and SOC of battery

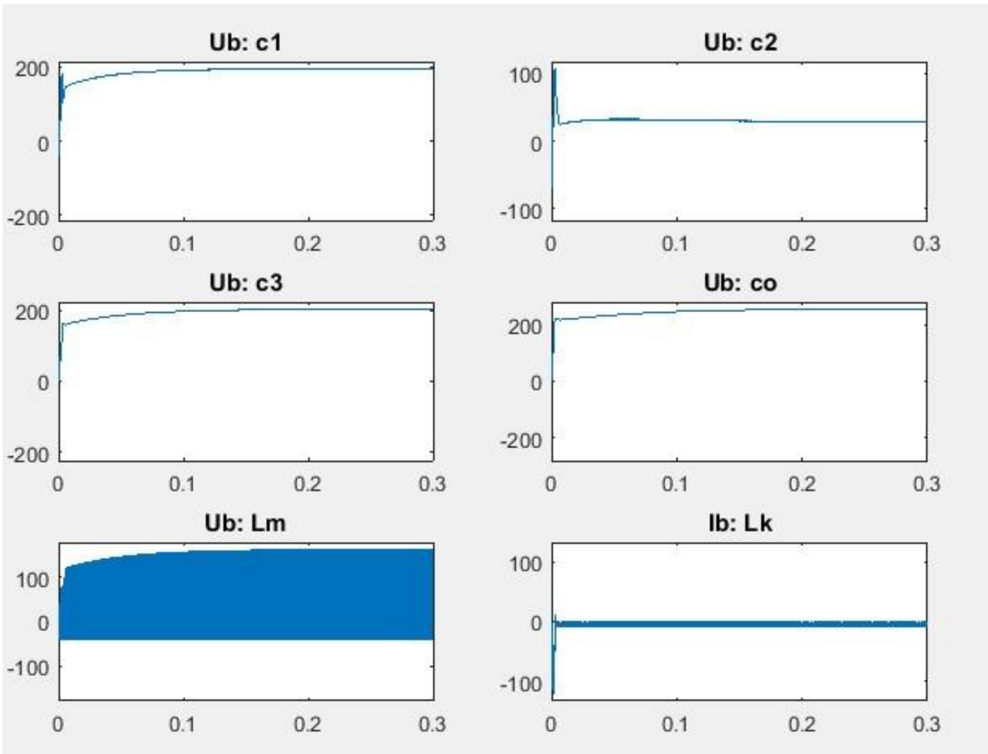

Figure 20 Capacitor Voltages and Inductor Currents

The voltages of the different capacitors show that the capacitors in the converter are charging and discharging continuously to keep the output load satisfied. We can also see that the current at the leakage inductance is fluctuating, this is because of the continuous charging and discharging of the clamp capacitor C_1. This happens in stages 4 and 5 where the inductances are also used to charge and discharge the capacitors.

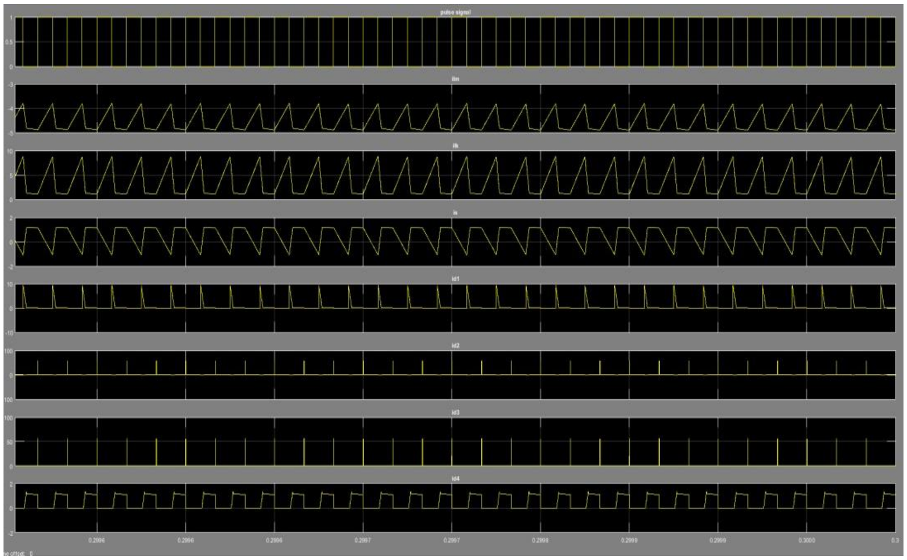

Figure 21 Diode Currents

The Diode currents show the way they are working, when observed closely, it is observable that when the diodes D_2 and D_3 have peaks the diodes D_1 and D_4 have valleys or are 0.

This shows the functionality of the converter and gives credibility to the CCM conduction mode studied in the section earlier. In the next section, converter applications with solar power is studied and further the solar power applications with the use of battery is also studied. The next chapter will have an in-depth consideration of the different Simulink models and the different attributes being used in each model.

Chapter 4: Testing and Studying the Proposed Converter Under Solar Power Conditions

4.1 Solar Module in Simulink

The PV module in Simulink is provided. This PV module data is provided by NREL. The PV module gives the exact amount of power that can be generated from the module at the specified irradiance and temperature. Higher temperature is not always suitable for the solar panel. The efficiency of the solar panel decreases significantly when the temperature of the module is high.

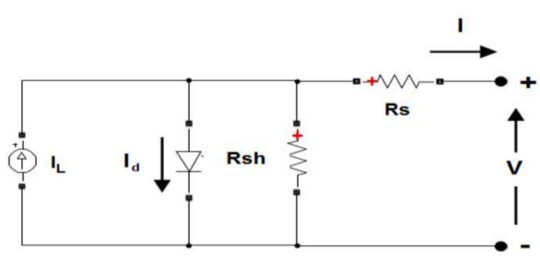

Figure 22 Circuit Diagram of pv module (M H Rashid, 2007)

4.2 Solar Power Application with the Converter

The Converter is tested under different input conditions, these input conditions is to provide an outlook as to how much voltage gain can the converter provide. This application of different loads will also provide an insight on how this converter can help in solar power applications.

Input Characteristics, the input characteristics show the amount of irradiance and temperature that is being provided to the solar panel.

Specified temperature: 25ºC

Specified irradiance: 1000,500,100

The irradiance is in a phase of stepping down, with decrements of 500 and then 400 respectively. The graph below shows the PV and IV characteristics of the PV module used in the first model.

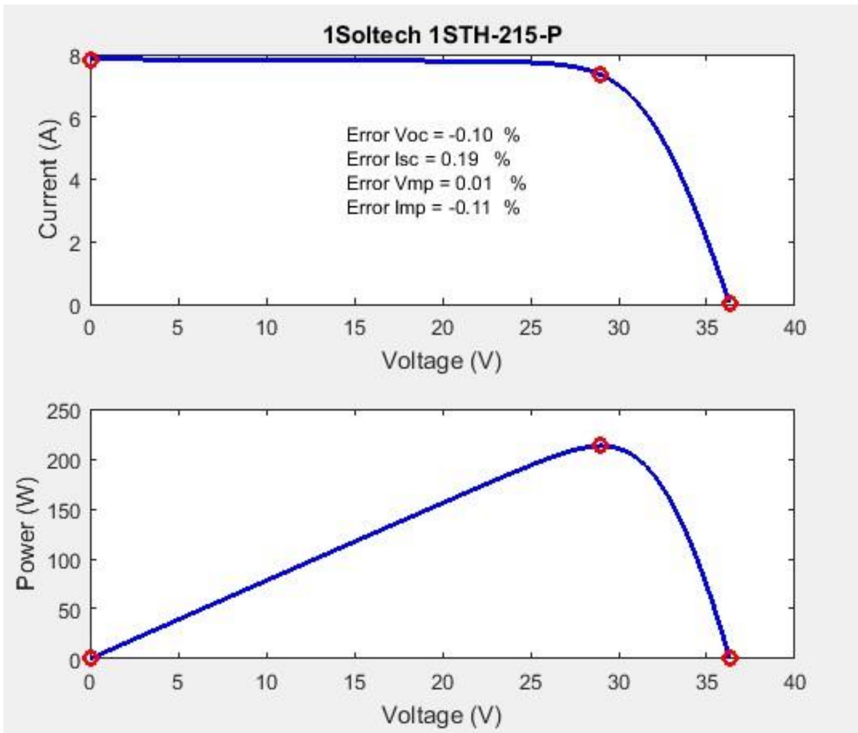

Figure 23 P-V and I-V characteristics of the PV module

4.2.1 Converter under LOW voltage PV module

1) The module used in the figure 4-4 is a 1 string-5 panels.
2) In the specified PV module the power being generated is at a maximum of 200 watts.
3) The voltage of this module is the best at 30V.
4) Current of the module is about 8 A approximately.

5) This power is very less but this condition is used to demonstrate the use of the converter at low power producing areas.

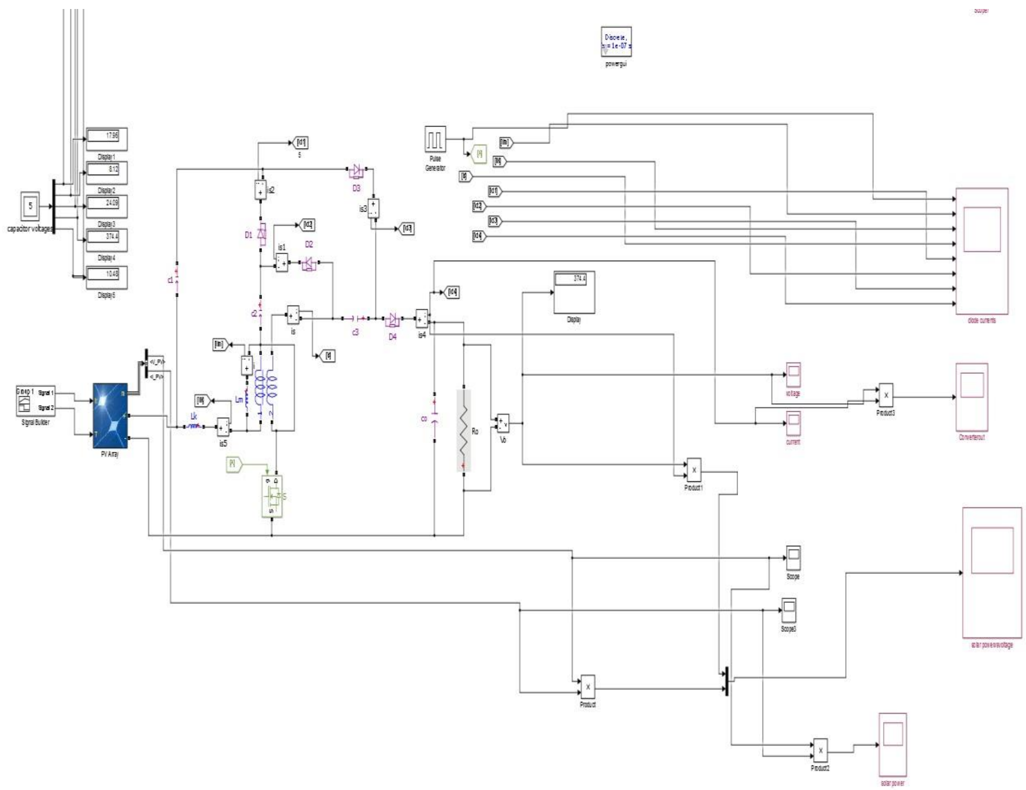

Figure 24 Converter with solar power application

Output characteristics: PV module

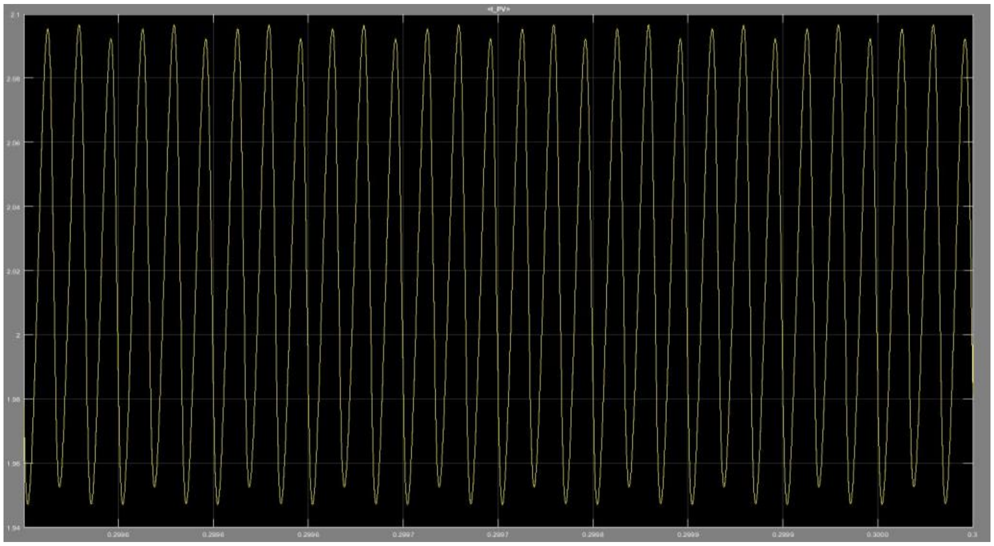

Figure 25 Converter with solar power application

1) Converter-Voltage

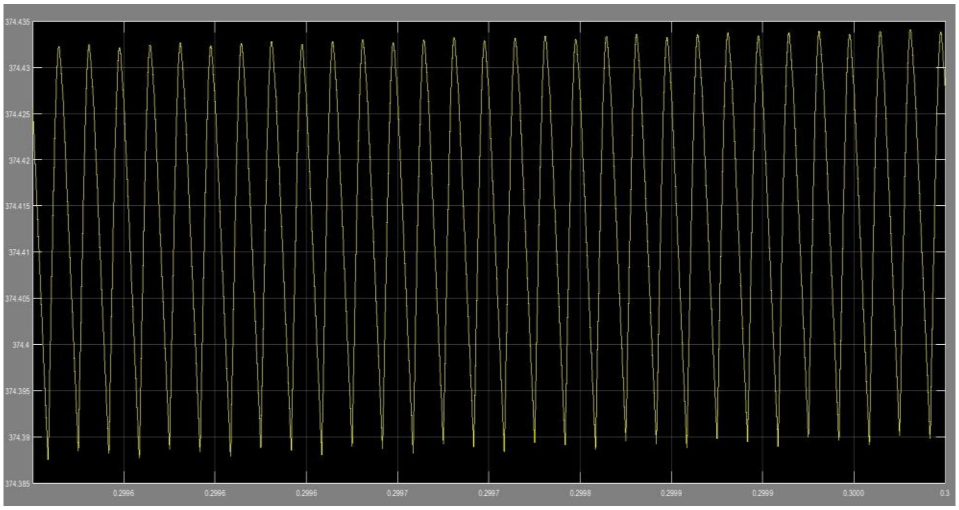

Figure 26 Converter Voltage

2) Capacitor voltages:

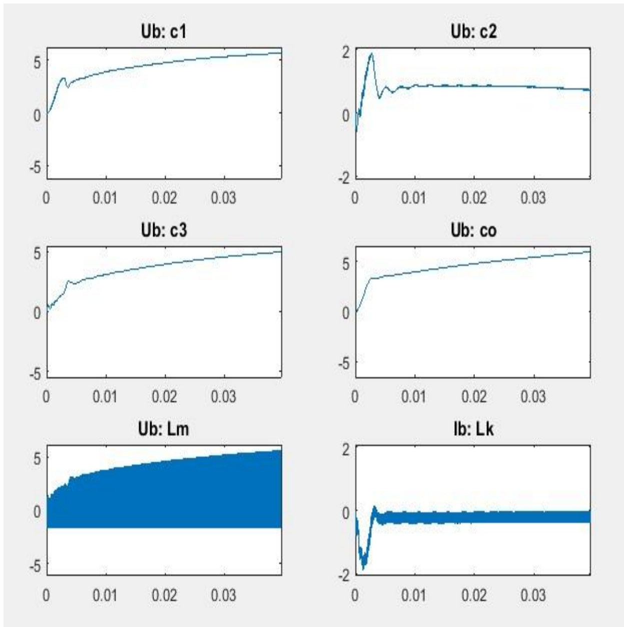

Figure 27 Capacitor Voltages

From the graphs in 1 and 2 we can see that the converter works perfectly with a small amount of solar power also, further the power of the PV module is increased to test the converter under high input characteristics.

4.2.2 Converter under High Voltage PV module

Input Characteristics for the converter under high i/p: The module is changed to having 10 parallel strings and 40 pv modules in each array. Therefore, this delivers an approximate voltage 1380V

• Diode Currents of the Converter under High Input

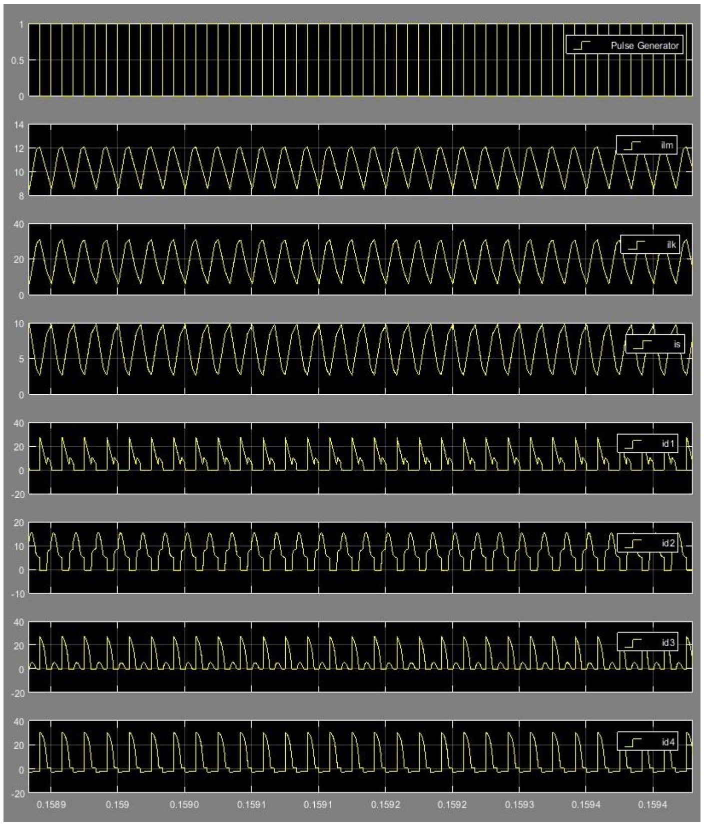

Figure 28 Diode currents if the converter is under high input

Capacitor voltages under high input

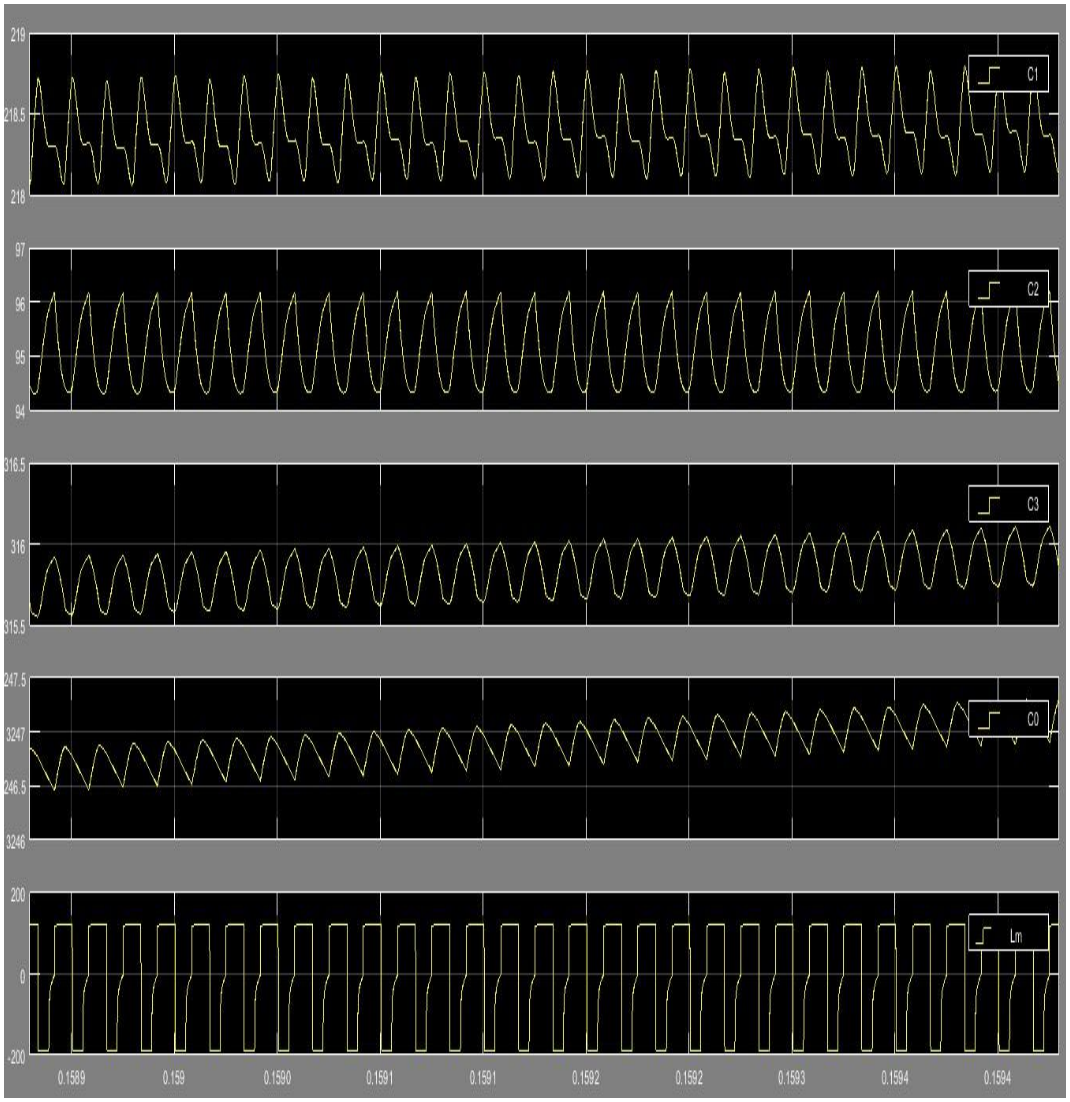

Figure 29 Capacitor Voltages

4.2.2.1 Results Discussion

The input by more ore used in the simulation has an output of 1380 volts which has been fed to the converter the converter in turn delivers a voltage of 3246 volts. From the graph of the diode currents it is a observable that the diodes work according to continuous conduction mode. In the graph of capacitor voltages, it is observable that the output voltage in each cycle is delivered by the output capacitor. It is also seen that capacitor 2 and 3 held charging the output capacitor.

4.3 Converter under Battery Charging

Conditions State of charge: 0%

Nominal Voltage: 1.2v

Voltage at full charge: 40v

Exponential zone: Voltage is 1.301 and Capacity

is 1.3Ah **Solar power Characteristics:**

1 parallel string with 5 in each string.

Output:

State of charge of battery:

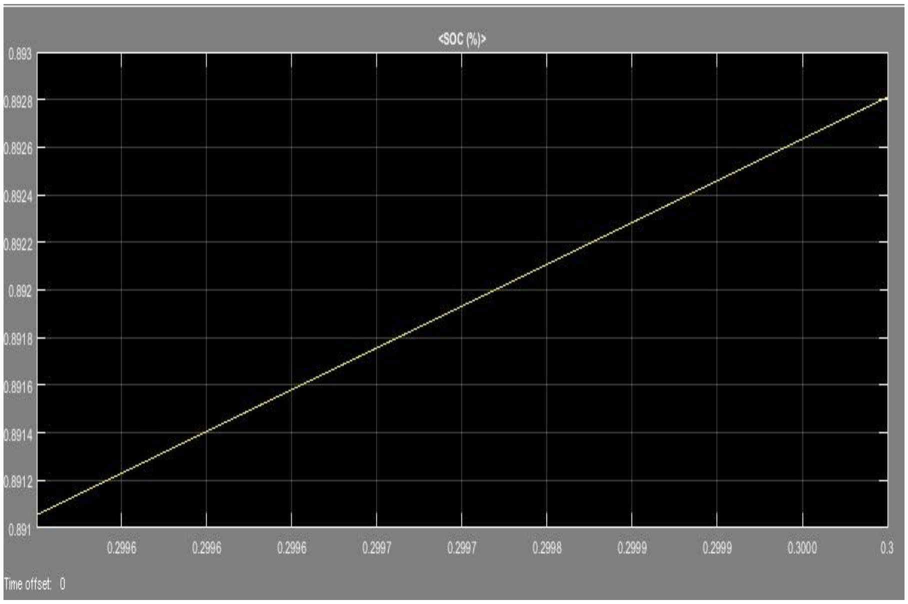

Figure 30 Figure shows the state of charge is increasing

Output of the converter:

Capacitor voltages of the converter

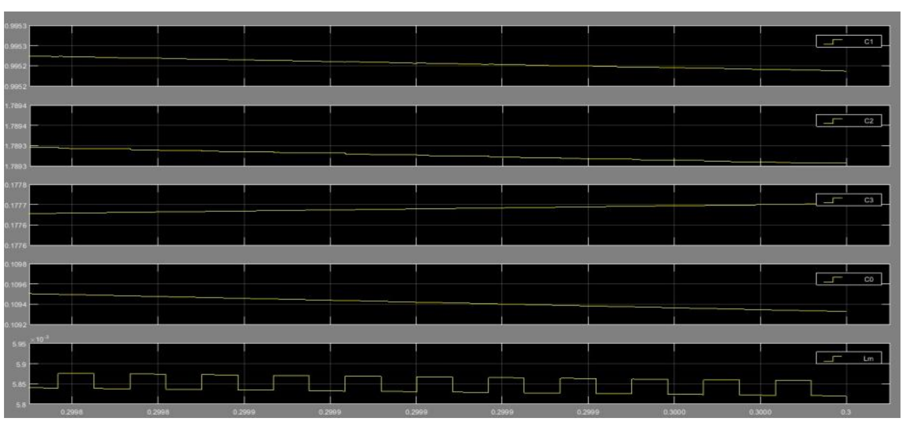

Figure 31 Capacitor voltages of the converter with battery connection

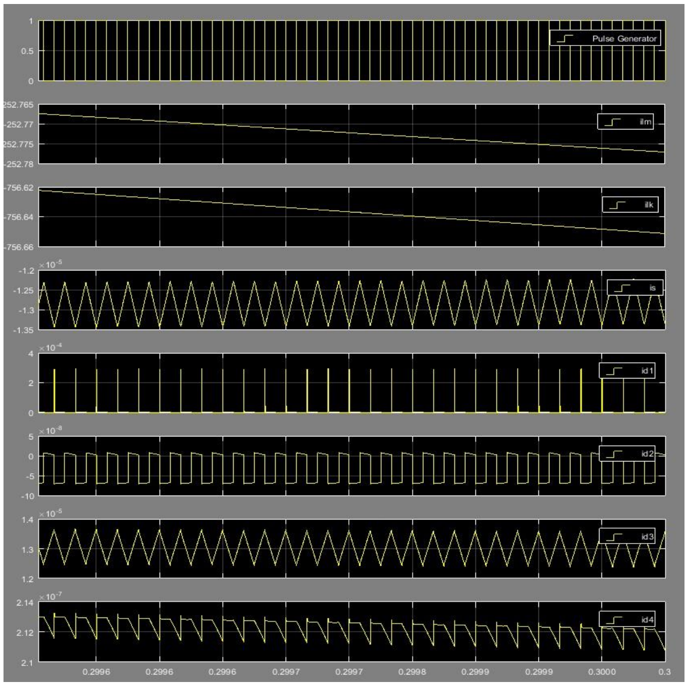

Figure 32 Diode currents of the converter

4.3.1.1 Result Discussion

Here the converter is tested under battery charging conditions. The battery initially has a zero percent charge. As the simulation starts, we can see that battery state of charge has raised up to user desired voltage, therefore showing the converters application in battery charging conditions. Also, from the current graph of the simulation, we can see that the leakage inductance and mutual inductance have negative current due to the battery charging. Furthermore, it is also observable that the currents in diode, 1, 2, 3 and 4 have very sharp peaks. This shows that the converter reacts quickly to changing conditions. The output voltage of the converter is maintained at 10 volts, which is a very good voltage, considering that the battery is at a zero percent charge.

4.4 Summary

- There are many different conditions under which the converter delivers a high voltage gain.
- In all the condition's output, the diode currents are shown. The diode currents show that the diodes follow the concept of the DC-DC converter with a coupled inductor.
- In all the cases where there is a battery connected, we can see that the output voltage is restricted to what the battery's output voltage is. But, the converter delivers a high voltage gain. The voltage output of the converter has variations in the range of 0.5v-1v.
- The switch voltage of the converter is seen to be varying the most as the leakage inductance and the mutual inductance keep charging and discharging the clamp capacitor

  C_1.
- While testing the converter with solar panel and a SOC of 0%, it was seen that the battery is charging heavily and also gives a high voltage gain.

- In the condition where the battery is fully charged and the converter is still powered by the solar panel the SOC of the battery does not change but the converter delivers a high voltage gain even with a very low input.
- In the final condition where the battery is fully charged and is the only source for delivering power, the SOC of the battery does not drop by much but the converter can utilize this amount of power to deliver a voltage gain upwards of 5.92 voltage gain
(V_o/V_{in}).

Chapter 5 Solar Power Installation

Introduction

The purpose of this chapter is to give a complete step by step of the different processes and parts involved in the installation and production of solar systems. Solar systems installation consists very importantly of 3 main parts.

1) Type of Ownership
2) Designing and possibility building
3) Permitting and Commissioning

The governments and policies have made the growth of solar power systems more viable and easier by mandating Net-Metering as an integral part of the solar system finances. Net metering helps in selling the excess amount of electricity back to the grid.(Ardani. Et al)

There are 2 main types of net-metering

1) Aggregate Net-metering

In this type of net-metering a consumer is allowed to add-up all the amount of excess solar energy productions, and sell back to the grid. The consumer in this case can add up all the production from his properties, including multiple meters. This is generally done in the residential solar power systems.

2) Virtual Net metering

In this type, all the production is first sold to the grid directly and the grid in-turn pays the facility of the production. This is generally done in bigger/commercial solar systems.

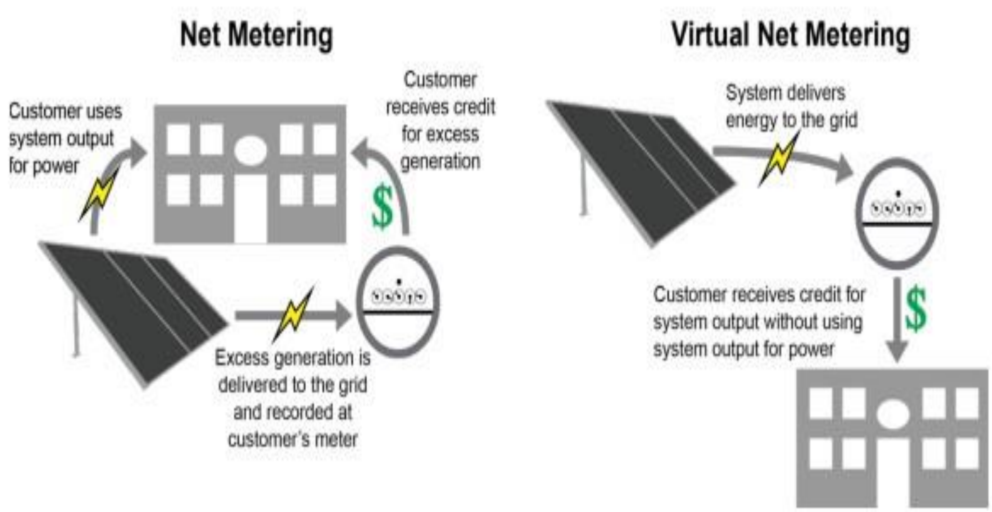

Figure 33 Comparison between net-metering and Virtual net-metering (Ardani et al. 2015)

There are 4 main factors that go into consideration of net-metering:

1) Maximum upper limit of allowed production: Where there is a limit of how big the system can be sized so as to avail a net-metering scheme for the system. Many states and utilities also have a 110% system size limit with reference to the usage of the consumer at site (Ardani. Et al).
2) Making Sure that the available rates are acceptable to the project economics, some states/utilities pay for the power delivered through the grid in form of RECs and some provide in terms of monetary benefits. The decision to get involved in the net-metering process heavily depends on the kind of project economics each kind of compensation projects (Ardani. Et al).
3) Many utilities around the country also have a limit on the aggregate amount of back-feeding that grid can take or will take. Net-metering will not be possible if the said utility has already met its goal for the amount of back-feeding it can take for the year or by the area.
4) The final factor in making the decision of net-metering depends on how the RECs are to be owned. RECs are renewable energy credits and can be owned by the owner of the system only. The credits can also be transferred from a single owner to the utility or to a third party that leases out the system/ power to a particular customer.

In the following parts of this chapter the different tasks of making a solar system possible will be discussed further.

5.1 Types of Ownership

There are many ways in which a solar power system can be owned. It can be owned by the consumer out-right or through different methods of

1) Third Party Ownership
2) Community Solar Share

5.1.1 Third part Ownership:

Third party ownership or TPO is when a consumer pays for the total output of a solar power system but the system is operated and maintained by a different entity. A general business model through which this is possible is known as the PPA (power purchase agreement), here a legal binding is made according to the consumer's needs and the third-party's goals. This contract is generally a 15-20-year term contract between the third party and the consumer. In this model the system itself may or may not be located at the site of consumption. (Ardani. Et al)

Many states have different policies regarding this business model. A few states regulate TPOs as utilities and few others characterize them as utilities but present different level of tariffs as it does not deliver the level of efficiency a utility grid otherwise might provide. In a few states, as a step towards encouraging solar, TPOs are not considered utility and separate rebates and credits are provided. This helps a small TPOs to function and also help bring down the total cost of a solar system.

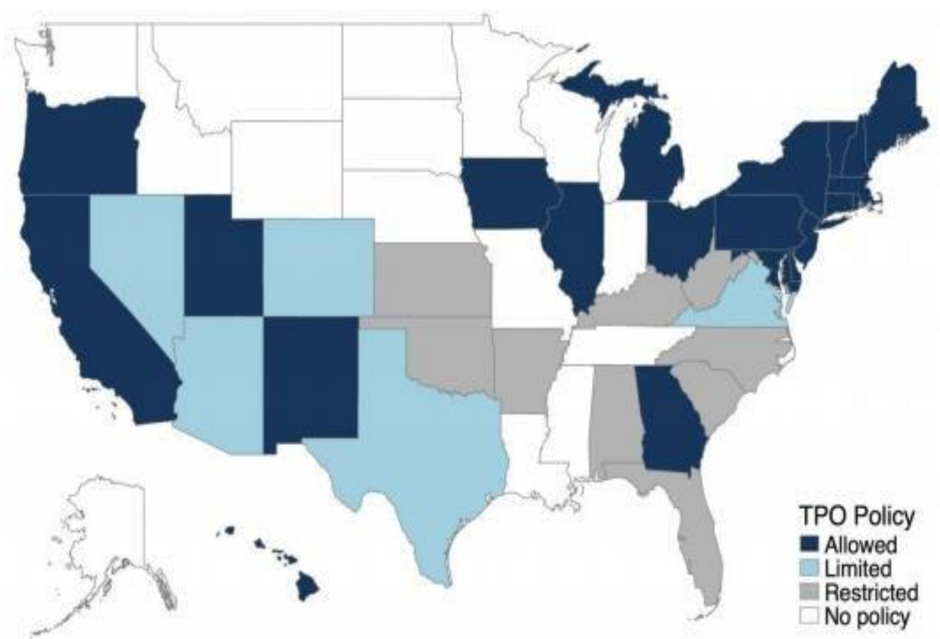

Figure 34 Regulation map for TPOs around the country (Ardani et al. 2015)

Characteristic to be checked before deciding on the type of interconnection:

1) Pre-existing policies:

As different states and zones have varied amount of pre-existing policies to regulate TPOs, it is necessary to look through all the legal implications and the rebate structure before going into a long-term contract with a company.

2) TPO's model and Incentive compatibility:

There may be many cases where there might arise a problem between the consumer being able to use to sell the state-based credits when one binds in a contract with a TPO. Some times the TPO may not be able to gain the REC credits from the consumer, this would drive the costs up for the consumer.

3) Though through the TPO business model many upfront costs can be negotiated and be written off, helping the consumer to avail green energy at zero upfront costs. The statebased REC credits play an important driver in the costs of the system. Consumers will, in many states, be able to negotiate at this stage where they are able to negotiate the ownership of the credits itself.

5.1.2 Community Solar Share

Community Solar share is a new newer business model in the solar market to be able to deliver solar power to consumers with a varied amount of problems pertaining to system costs, space availability and state legislation. (Ardani. Et al) There are three main types of community solar share:

1) Many utilities around the country own and operate their own solar gardens, further there are many options for the consumers of the utility itself to buy in on the solar share and be able to avail recreational solar credits. These contracts can be a long-term or a short-term buy in.
2) For consumers in groups and for commercial consumers, many times, the state allows for them to invest in a solar farm and receive incentives in reference to the amount of investment the group has made.

3) The final model of solar share programs is the non-profit model where the organizations seek funds from the market to develop solar farms so as to distribute electricity to a minority group at a lower and a more affordable price. The donors might or might not seek recreational energy credits and state given incentives from the project they donated towards.

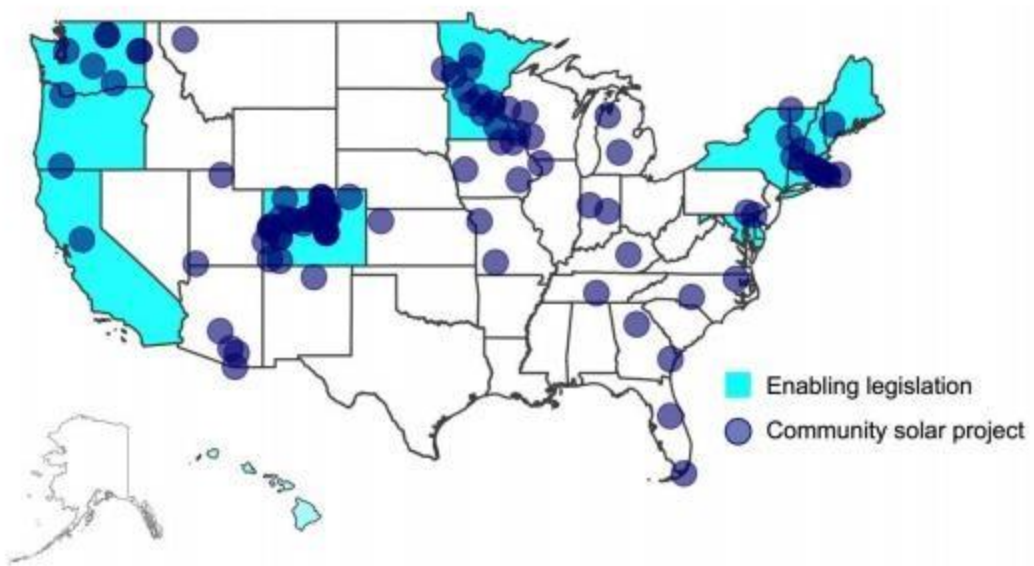

Figure 35 Community Solar Map of states with and Without Legislation (Ardani et al. 2015)

There are many states where the legislation and state-based incentives are still developing towards the community solar share program, but as seen from figure 3, there are projects being developed and maintained in states which have pre-existing legislation towards the program and also in states that do no have any legislation around the community solar share program.

5.2 Designing and Possibility Building

The second important task in building a solar power system is to design a solar system with in the regulations of the state/district and the home owners authority legislation that the said site of install is located in.

There are 3 main steps in the designing of an acceptable solar system

1) Heat and obstruction map
2) Preliminary design
3) 3-line diagram

5.2.1 Heat and Obstruction map

This is the first stage in the designing of a viable system, in this process the availability of sunlight is measured and an analysis is made on many factors as to what amount of offset is possible to establish at the site of install

1) The first step of this task is to measure the amount of irradiance and map out obstructions around the house that might be blocking Irradiance coming onto the Solar system

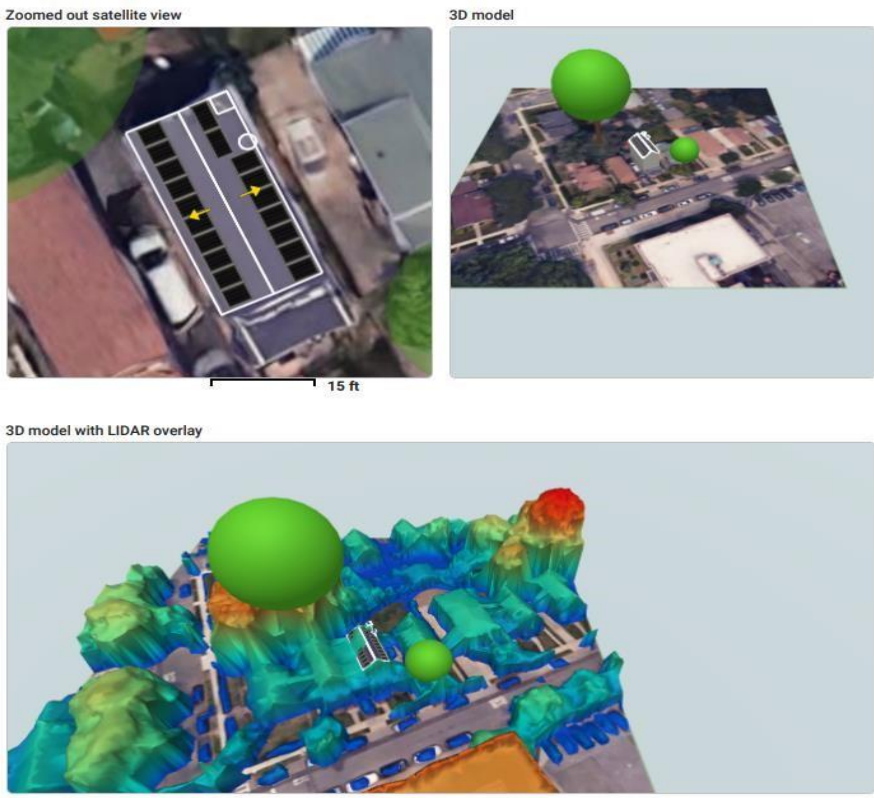

Figure 36 Image showing the said address mapped out with obstructions on the roof and around the site using Aerial/ 3-D maps and LIDAR (Light Detection and Ranging)

2) Second step is to make an approximate system design using the aerial data available from step 1.

Summary

Array	Panel Count	Azimuth (deg.)	Pitch (deg.)	Annual TOF (%)	Annual Solar Access (%)	Annual TSRF (%)
1	9	65	33	70	83	58
2	10	245	37	88	93	82
Weighted average by panel count	-	-	-	-	88.4	70.7

Monthly solar access (%) across arrays

Array	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	75	73	78	84	87	88	88	87	82	74	74	74
2	94	95	95	95	91	87	89	96	95	96	94	95

Figure 37 Design with irradiance availability at site and with production availability during different months.

This step involves the analysis of TSRF factors which takes into consideration factors like shading, tilt of site and orientation factor of the site itself. These factors help in understanding whether or not a project will be efficient both power offset-wise and financially.

5.2.2 Preliminary Design

Preliminary design is the step in the process where the possible power usage offset is acceptable by the consumer and by the state-legislation itself. Here the system will have to follow the regulations of different jurisdictions like the electric codes and fire codes of the state.

Here a CAD software is used to develop a design to affirm the obstruction map and also the space availability for the system.

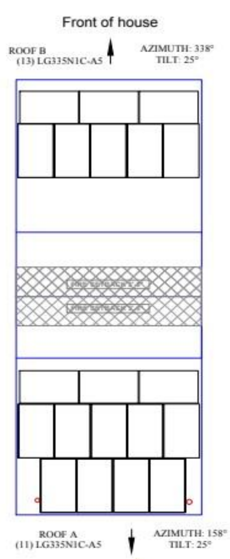

Figure 38 Prelim Design Using CAD software

Here the different determined components are shown on the design:

1) Obstructions (marked in red)
2) Site Outline (marked in blue)
3) Solar Panels location on the site (marked in black)
4) Fire code offset (marked in grey)
5) Nomenclature of each side of the site with panels with data of the tilt, orientation and azimuth angle.

5.2.3 3-Line Diagram

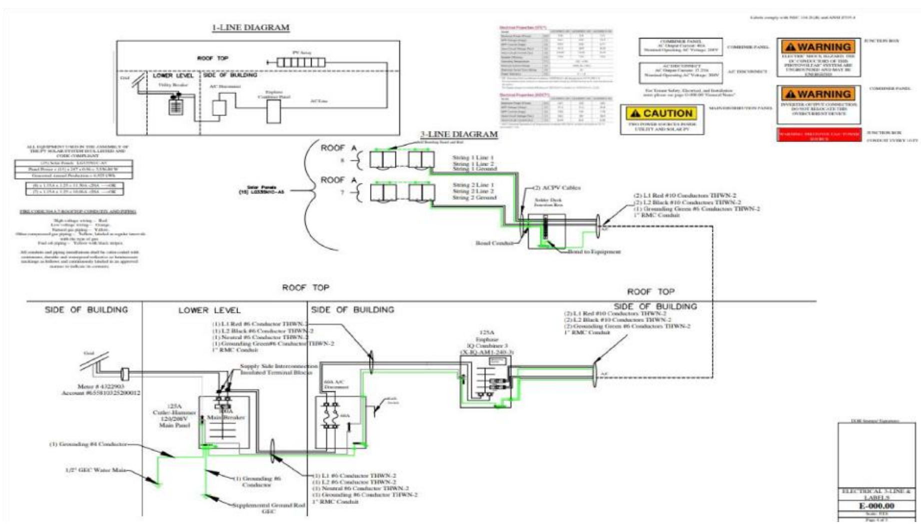

Figure 39 3-Line Diagram showing different parts of the system

The Different parts of the 3-line CAD design are:

1) Solar panel, string interconnection and total power out let.

2) Interconnection from the panels to the Inverter.

3) Inverter to Disconnect connection.

4) Disconnect to Main service panel connection.

5) Interconnection from service panel to the point of back-feeding into the utility grid.

6) Nomenclature showing the different electrical components of the design at different points.

7) Nomenclature showing warnings and different legislature rules and laws the system is following and adhering to.

5.3 Permitting and Commissioning

This is the final task in making a solar system a possibility. Permitting is a step that is done before the installation of the project itself. Here the designs are submitted to the jurisdiction for stamping and acquiring the go-ahead on any project.

Commissioning is a step after the installation where an inspector from the different jurisdictions are made available at the site of install to be able to certify the install of the project. After the utility is able to verify the different regulations the project is commissioned and operated to deliver the desired offset. (Ardani. Et al)

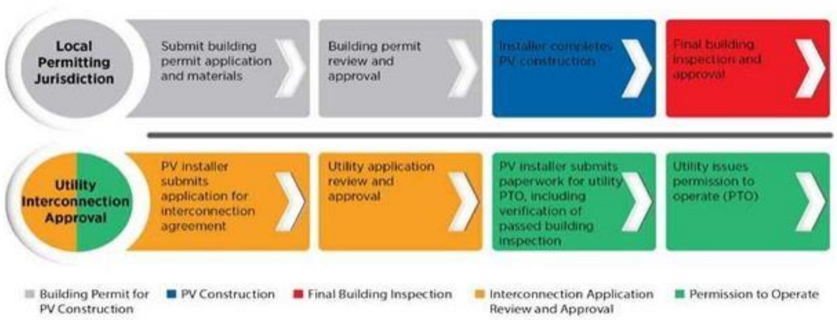

Figure 40 Showing the different steps involved in permitting and commissioning a solar system (Ardani et al. 2015)

Chapter 6: Conclusion and Future work

6.1 Conclusion

The thesis provides a discussion into the challenges faced by centralized generation and distributed generation. In distributed generation, different types are considered and evaluated. This study has helped realizing the advantages and disadvantages of solar power. A challenge is considered and a solution is studied and tested with the help of Matlab/Simulink.+

The presented converter as seen works perfectly well with solar power applications it also works well with battery charging conditions.

The converter can deliver a high amount of gain even with small strings of solar modules. In solar strings of even 5 modules, the converter was able to accept the low level of input while being able to deliver the level of output need for interconnection. This goes to show that the converter has heavy applications in fast charging systems, the converter is also applied to the PV module at zero percent charge, showing that the PV module can charge the battery as well as deliver a high voltage due to the converter, which responds to the low input by providing high voltage gain.

The converter helps distributed generation a lot because it delivers a high voltage gain even at lower voltage inputs, therefore showing that the converter can be applied to each and every module in the array further, giving a higher voltage gain. Also, the converter can give a high voltage gain that the PV module can be connected to the main utility grade. It is also seen that the voltage at the switch is very low.

Therefore, this converter provides a high voltage gain and delivers less current at the switch and also stabilizes the output current. The leakage inductance and the magnetizing inductance help in delivering a varied amount of current, therefore giving the user more opportunity to control and modulate the amount of power one needs.

6.2 Future Work

This thesis conducts a validation process towards using distributed generation instead of centralized generation. Future work may include:

1) Building a robust network which can accommodate the influx of high penetration of distributed generation.

2) Control measures for voltage of distributed generation needs to be further studied.

3) A detailed model, which incorporates the presented converter and the grid needs to be built and tested.

4) Calling for policy change in many states that would mandate the use or part-take in solar power production.

References

[1].F.Nejabatkhah, S. Danyali, S. Hosseini, M. Sabahi, and S. Niapour, "Modeling and control of a new three-input DC–DC boost converter for hybrid PV/FC/battery power system," IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2309–2324, May 2012.

[2].R. J. Wai and K. H. Jheng, "High-efficiency single-input multiple-output DC–DC converter," IEEE Trans. Power Electron., vol. 28, no. 2, pp. 886–898, Feb. 2013.

[3].Y. Zhao, X. Xiang, C. Li, Y. Gu, W. Li, and X. He, "Single-phase high step-up converter with improved multiplier cell suitable for half- bridgebased PV inverter system," IEEE Trans. Power Electron., vol. 29, no. 6, pp. 2807–2816, Jun. 2014.

[4].J.H. Lee, T. J. Liang, and J. F. Chen, "Isolated coupled-inductor-integrated DC–DC converter with non-dissipative snubber for solar energy applications," IEEE Trans. Ind. Electron., vol. 61, no. 7, pp. 3337–3348, Jul. 2014.

[5].C.Olalla, C. Delineand, andD.Maksimovic, “Performance ofmismatched PV systems withsubmodule integrated converters,” IEEE J. Photovoltaic, vol. 4, no. 1, pp. 396–404, Jan. 2014.

[6].C. W. Chen, K. H. Chen, and Y. M. Chen, “Modeling and controller design of an autonomous PV module for DMPPT PV systems,” IEEE Trans. Power Electron., vol. 29, no. 9, pp. 4723–4732, Sep. 2014.

[7].Y. P. Hsieh, J. F. Chen, T. J. Liang, and L. S. Yang, “Analysis and implementation of a novel single-switch high step-up DC–DC converter,” IET Power Electron., vol. 5, no. 1, pp. 11–21, Jan. 2012.

[8].Y. Zhao, W. Li, Y. Deng, and X. He, “High step-up boost converter with passive lossless clamp circuit for non-isolated high step-up applications,” IET Power Electron., vol. 4, no. 8, pp. 851–859, Sep. 2011.

[9].I. Laird and D. D. Lu, “High step-up DC/DC topology and MPPT algorithm for use with a thermoelectric generator,” IEEE Trans. Power Electron., vol. 28, no. 7, pp. 3147–3157, Jul. 2013.

[10].R. J. Wai, C. Y. Lin, C. Y. Lin, R. Y. Duan, and Y. R. Chang, “Highefficiency power conversion system for kilowatt-level stand-alone

generation unit with low input voltage," IEEE Trans. Ind. Electron., vol. 55, no. 10, pp. 3702–3714, Oct. 2008.

[11].L. S.Yang,T. J. Liang, and J. F.Chen, "Transformer-lessDC–DCconverter with high voltage gain," IEEE Trans. Ind. Electron., vol. 56, no. 8, pp. 3144–3152, Aug. 2009.

[12].Y. P. Hsieh, J. F. Chen, T. J. Liang, and L. S. Yang, "Novel high step-up DC–DC converter with coupled-inductor and switched-capacitor techniques," IEEE Trans. Ind. Electron., vol. 59, no. 2, pp. 998–1007, Feb. 2012.

[13].J. A. Carr, D. Hotz, J. C. Balda, H. A. Mantooth, A. Ong, and A. Agarwal, "Assessing the impact of SiC MOSFETs on converter interfaces for distributed energy resources," IEEE Trans. Power Electron., vol. 24, no. 1, pp. 260–270, Jan. 2009.

[14].C. L. Wei and M. H. Shih, "Design of a switched-capacitor DC-DC converter with a wide input voltage range," IEEE Trans. Circuits Syst., vol. 60, no. 6, pp. 1648–1656, Jun. 2013.

[15].W. Qian, D. Cao, J. G. C. Rivera, M. Gebben, D.Wey, and F. Z. Peng, “A switchedcapacitor DC–DC converter with high voltage gain and reduced component rating and count,” IEEE Trans. Ind. Electron., vol. 48, no. 4, pp. 1397–1406, Jul. 2012.

[16].Y. P. Hsieh, J. F. Chen, T. J. Liang, and L. S. Yang, “Novel high step-up DC–DC converter with coupled-inductor and switched-capacitor techniques,” IEEE Trans. Ind. Electron., vol. 59, no. 2, pp. 998–1007, Feb. 2012.

[17].T. J. Liang, J. H. Lee, S. M. Chen, J. F. Chen, and L. S. Yang, “Novel isolated highstep-up DC–DC converter with voltage lift,” IEEE Trans. Ind. Electron., vol. 60, no. 4, pp. 1483–1491, Apr. 2013.

[18].F. L. Luo and H. Ye, “Hybrid split capacitors and split inductors applied in positive output super-lift Luo-converters,” IET Power Electron., vol. 6, no. 9, pp. 1759–1768, Jun. 2013.

[19].T. J. Liang, J. H. Lee, S. M. Chen, J. F. Chen, and L. S. Yang, “Novel isolated highstep-up DC–DC converter with voltage lift,” IEEE Trans. Ind. Electron., vol. 60, no. 4, pp. 1483–1491, Apr. 2013.

[20].W. Li, W. Li, X. Xiang, Y. Hu, and X. He, “High step-up interleaved converter with built-in transformer voltage multiplier cells for sustainable energy applications,” IEEE Trans. Power Electron, vol. 29, no. 6, pp. 2829–2836, Jun. 2014.

[21].X. Hu and C. Gong, “A high voltage gain DC-DC converter integrating coupledinductor and diode-capacitor techniques,” IEEE Trans. Power Electron., vol. 29, no. 2, pp. 789–800, Feb. 2014.

[22].T. F. Wu, Y. S. Lai, J. C. Hung, and Y. M. Chen, “Boost converter with coupled inductors and buck–boost type of active clamp,” IEEE Trans. Ind. Electron., vol. 55, no. 1, pp. 154–162, Jan. 2008.

[23].L. S. Yang, T. J. Liang, H. C. Lee, and J. F. Chen, “Novel high step-up DC–DC converter with coupled-inductor and voltage-doubler circuits,” IEEE Trans. Ind. Electron., vol. 58, no. 9, pp. 4196–4206, Sep. 2011.

[24].K. C. Tseng and C. C. Huang, “High step-up, high efficiency interleaved converter with voltage multiplier module for renewable energy system,” IEEE Trans. Ind. Electron., vol. 61, no. 3, pp. 1311–1319, Mar. 2014.

[25].K. I. Hwu and W. Z. Jiang, "Voltage gain enhancement for a step-up converter constructed by KY and buck-boost converters," IEEE Trans. Ind. Electron., vol. 61, no. 4, pp. 1758–1768, Apr. 2014.

[26].T. J. Liang, S. M. Chen, L. S. Yang, J. F. Chen, and A. Ioinovici, "Ultralarge gain step-up switched-capacitor DC-DC converter with coupled inductor for alternative sources of energy," IEEE Trans. Circuits Syst., vol. 59, no. 4, pp. 864–874, Apr. 2012.

[27].Ackermann, T., Andersson, G., S.oder, L., (2001). "Distributed generation: a definition". Electric Power Systems Research 57, pp. 195–204.

[28].Arndt, U., Wagner, U., (2003). "Energiewirtschafltiche Auswirkungen eines Virtuellen Brennstoffzellen-Kraftwerks".

[29].VDI-Berichte. Carley, S., (2009). "Distributed generation: an empirical analysis of primary motivators". Energy Policy, 37, pp. 1648 – 1659. Chambers, A., (2001). Distributed generation: a nontechnical guide. PennWell, Tulsa, OK, pp. 283.

[30].Cossent,R., Gomez T., Frias, P., (2009). "Towards a future with large penetration of distributed generation: Is the current regulation of electricity

distribution ready? Regulatory recommendations under a European perspective". Energy Policy, 37,pp. 1145- 1155.

[31].Costa, M.P., Matos, M.A., Pecas Lopes, J.A., (2008). "Regulation of microgeneration and microgrids". Energy Policy, 36, pp. 3893 - 3904.

[32].Dondi, P., Bayoumi, D., Haederli, C., Julian, D., Suter, M., (2002). "Network integration of distributed power generation". Journal of Power Sources 106, pp. 1–9. DGTW., (2008). 2008 32nd Power Generation Order Survey, Diesel and Gas Turbine Worldwide (http://www.dieselgasturbine.com/pdf/power_2008.pdf#zoom=100).
EIA (2009). Monthly energy review March 2009. Energy Information Administration., (http://www.eia.doe.gov/mer).

[33].El-Kattam,W., Salama, M.M.A, (2004). "Distributed Generation Technologies: definitions and benefits". Electric Power Research, 71, pp. 119-128. 38 European Communities, 2006. Communication from the Commission to the European Council and the European Parliament. COM (2006) 545 final. "Action Plan for Energy Efficiency: Realizing the Potential".

(http://ec.europa.eu/energy/action_plan_energy_efficiency/doc/com_2006_0545_en.p df).

[34].Feldmann, W., (2002). “Dezentrale Energieversorgung-zukünftige Entwicklungen, technische Anforderungen”. Conference; Energie Innovativ 2002.

[35].VDI Verlag, Düsserldorf. Hirsh, R.F., (1989). Technology and Transformation in the American Electric Utility Industry, Cambridge University Press: New York, New York.

[36].International Energy Agency, (2002). Distributed Generation in a liberalized energy market. Jouve: France. International Energy Agency, (2003). “Distributed Generation and Renewables Outlook 2030”, (http://www.iea.org/textbase/work/2004/distgen/Birol.pdf).

[37].Intergovernmental Panel on Climate Change (IPCC), (2007). Climate Change 2007 Mitigation of Climate Change: Working Group III contribution to the Fourth Assessment Report of the IPCC (Climate Change 2007), IPCC, Cambridge University Press. Jänig, C., (2002). “Perspektive. Lokal Energie – Geschäftsbericht 2001”.

[38].Stadtwerke Unna GmbH, Unna. Jenkins, N., Allan, R., Kirschen, D., Strbac, G.,(2000). Embedded Generation.

[39].Institution of Electrical Engineers (IEE), London. Jörss, W., Jorgensen, B.H., Löffler, P., Morthorst, P.E., Uyterlinde, M., Sambeek, E., Wehnert, T., (2003). Decentralized Power Generation in the Liberalized EU Energy Markets. Springer: Berlin Heidelberg New York. 39 Lehtonen, M., Nye, S., (2009). "History of electricity network control and distributed generation in the UK and Western Denmark". Energy Policy, doi:10.1016/j.enpol.2009.01.026.

[40].McDonald, J., (2008). "Adaptive intelligent power systems: active distribution networks". Energy Policy 36, pp. 4346–4351.

[41].Mendez, V.H., Rivier, J., de la Fuente, J.I, Gomez, T., Arceluz, J., Marin, J., (2002). Impact of Distributed Generation on Distribution >etwork. Universidad Pontificia Comillas, Madrid.

[42].OFGEM, 2007. "Review of Distributed Generation". Office of Gas and Electricity Markets (www.dti.gov.uk/energy/whitepaper).

[43].Pehnt, M., (2006). “Micro Cogeneration Technology”, in Pehnt, M., Cames, M., Fischer, C., Praetorius, B., Shneider, L., Schumacher, K., Voss, J.P. Micro cogeneration towards decentralized energy systems, Berlin: Springer, pp. 197-218.

[44].Pehnt, M., Schneider, L., (2006). “Embedding Micro Cogeneration in the Energy Supply System”, in Pehnt, M., Cames, M., Fischer, C., Praetorius, B., Shneider, L., Schumacher, K., Voss, J.P. Micro cogeneration towards decentralized energy systems, Berlin: Springer, pp. 197-218.

[45].Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., D’haeseleer, W., (2005). “Distributed Generation: definition, benefits and issues”. Energy Policy, 33, pp. 787- 798.

[46].Praetorius, B., (2006). “Micro Cogeneration – Setting of an Emerging Market”, in Pehnt, M., Cames, M., Fischer, C., Praetorius, B., Shneider, L., Schumacher, K., Voss, J.P. Micro cogeneration towards decentralized energy systems, Berlin: Springer, pp. 145-170.

[47].Rawson, M.,Sugar J., (2007). “Distributed Generation and Cogeneration policy roadmap for California”. California Energy Commission

(http://www.energy.ca.gov/2007publications/CEC-500-2007-021/CEC-500-2007- 021.PDF).

[48].Stephanblome, T., Bühner, V., (2002). "Virtuelles Kraftwerk: Energiewirtschafliche Voraussetzungen & Leittechnick-Software". Conference: Energie Innovativ 2002. VDI Verlag, Düsseldorf.

[49].Strachan, N., Farell, A., (2006). "Emissions from distributed vs. Centralized generation: the importance of system performance". Energy Policy 34, pp. 2677- 2689.

[50].US DOE, (2007). "The Potential Benefits of Distributed Generation and raterelated issues that may impede their expansion. A Study pursuant to Section 1817 of the Energy Policy Act of 2005".US Department of Energy.

[51].US EPA., (2003). Inventory of US Greenhouse Gas Emissions and Sinks: 1990– 2001. EPA 430-R-03-004. US Environmental Protection Agency, Washington, DC.

[52].WADE., (2006). "World Survey of Decentralized Energy, 2006". World Alliance for Decentralized Energy. (http://www.localpower.org/nar_publications.html).

[53].Woodman, B., Baker, P., (2008). “Regulatory framework for decentralised energy. Energy Policy” 36 , pp. 4527–4531.

[54].Ardani, Kristen, Carolyn Davidson, Robert Margolis, and Erin Nobler, 2015. “A state-level comparision of processes and timelines for Distributed Photovoltaic Interconnection in the United States” National renewable Energy Labarotary. http://www.nrel.gov/docs/fy15osti/63556.pdf.

[55].Bolinger, Mark. 2009. Financing Non-Residential Photovoltaic Projects: Options and Implications. Berkeley, CA: Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/all/files/report-lbnl1410e.pdf